BOOSTER
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Foreword

The original Booster rookie book was written in 1980 by John Crawford and used by Operators for 13 years as the principal document to familiarize themselves with Booster hardware and operations. The LINAC 400 MeV Upgrade and the numerous changes that accompanied it provided the final push to write a new version.

The next version, completed in December 1993, borrowed from the original text on systems that had not changed. The finished book was a combined effort of a number of people: Bill Pellico, Jim Morgan, Cons Gattuso, and Juan Reyna.

This third version, completed in November of 1998, was necessitated by changes in the Booster due to the Main Injector. The current rewrite couldn't have been accomplished without the help of Brian Drendel, Todd Sullivan, Chuck Broy, and many others.

Bruce Worthel
December 1998

Introduction

The FNAL Booster accelerator is approximately 150-meter diameter proton synchrotron with an injection energy of 400 MeV and an extraction energy of 8 GeV. It is considered a “fast cycling” machine, cycling at 15 Hz. A resonant power supply system uses a sinusoidal current waveform to excite the magnets. The Booster is made up of 96 combined function magnets in a series of 24 repeating periods. Their magnetic field varies from about 740 gauss at injection to 7,000 gauss at extraction. The Booster tunnel is a concrete tunnel 8 feet high and 10 feet wide, covered by 15 feet of earth shielding.

The 400 MeV line transfers the beam from LINAC to the Booster, bending the beam vertically fifteen feet. A multiple turn system increases the Booster intensity by stacking successive turns of LINAC beam layered on top of each other. RF (radio frequency) energy, delivered by up to 17 ferrite-tuned cavity resonators, accelerates the proton beam over the 33 msec rising portion of the sinusoidal current waveform. Beam can be extracted from Booster at two locations, depending on its destination. An extraction at Long 13 transfers beam to the Booster dump. An extraction at Long 3, initiated by kickers in Long 2, transfers beam to the Main Injector via the MI-8 line.

Booster Parameters

Circumference	2π x 74.47 meters
Injection energy	400 Mev (kinetic)
Extraction energy	8 Gev (kinetic)
Cycle time	1/15 sec
Harmonic number, h	84
Transition gamma	5.45
Injection Frequency	37.77 Mhz
Extraction Frequency	52.81 Mhz
Maximaum RF voltage	0.86 MV
Longitudinal emittance	0.25 eV sec
Horizontal β max	33.7 meters
Vertical β max	20.5 meters
Maximum dispersion	3.2 meters
Tune $\upsilon x = \upsilon y$	6.7
Transverse emittance(normailized)	12π mm rad
Bend magnet length	2.9 meters
Standard cell length	19.76 meters
Bend magnets per cell	4
Bend magnets total	96
Typical bunch intensity	3 x 10e10
Phase advance per cell	96 degs
Cell type	FOFDOOD (DOODFOF)

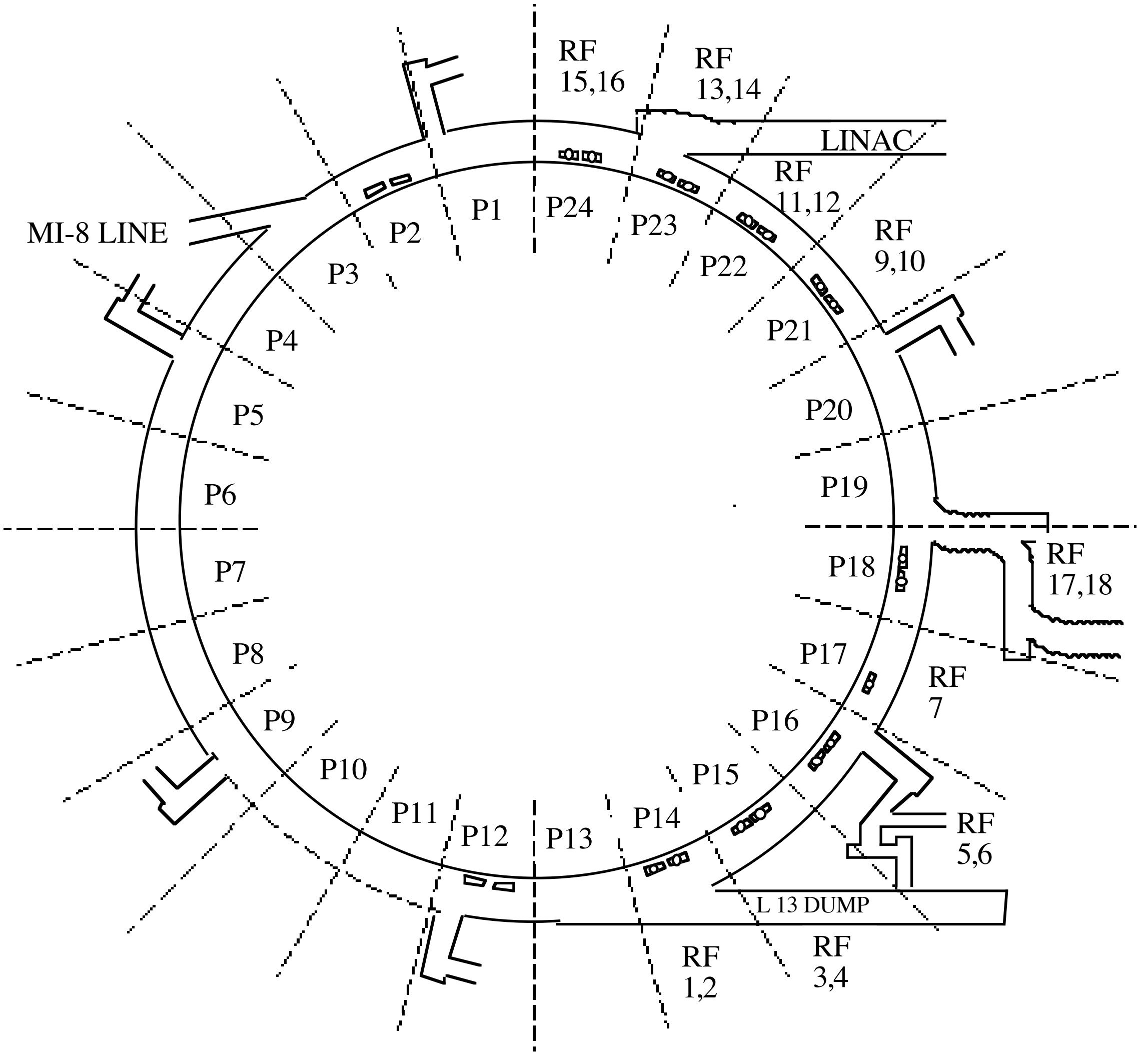
Booster History and Design

Most proton synchrotrons built before Fermilab came into existence used a linear accelerator to inject protons directly into the main accelerator. With the design of original Fermilab Main Ring, which had a final energy that was much larger than existing accelerators, that scheme was incompatible. A linear accelerator capable of accelerating protons to the 8-GeV injection energy of the Main Ring would have had to be nearly four miles long—an impractical and expensive option. Lowering the injection energy of the Main Ring wasn't a good option either. It would have been very difficult and expensive to design a ring that would exhibit a stable guide field at low field and behave well at 400 GeV. As with present day accelerator design, cost was the major motivation for the creation and final design of the Booster accelerator.

Because of the existing problems, it was decided that a "booster accelerator" would give an intermediate boost to the beam energy between the LINAC and the Main Ring. The first design parameter investigated was the injection and extraction energies of the Booster ring. One of the main factors affecting the injection energy was the cost of the LINAC versus the cost of the Booster RF. As LINAC energy increased, the Booster RF requirements were reduced. Although the lowest cost combination was something less than the 200 MeV energy eventually selected, the modest cost increase was considered worth the increase in beam quality. The Main Ring cost analysis originally set the extraction energy of Booster to 10 GeV. However, subsequent analysis estimated savings of over $500,000 when the final energy was reduced to 8 GeV. In this case, the small degradation in beam quality was considered worth the large cost reduction. The gradient magnet power supply has been upgraded from its original design, but it is still capable of running Booster to 10 GeV.

With the injection energy decided upon, several designs were proposed for the Booster with the main differences involving the radius and the cycling time. Due to the high cost of construction and possible destructive resonance phenomena, the idea of a large radius Booster was abandoned in favor of a much smaller machine. (The final design resulted in a circumference 13.25 times smaller than the Main Ring.) The Booster is 1/7 the size of the Main Injector. To fill the Main Injector with beam, the Booster must go through repeated acceleration cycles, transferring each cycle's worth of beam. Each of the extracted beam pulses is referred to as a "batch." (The Booster was capable of delivering 15 of these batches each second, but the PreAcc pulse shifter allowed only 13 pulses before it inhibited the beam. In actuality, only 12 batches were injected into the Main Ring, as a gap had to be preserved in the beam to allow time for kickers to rise to their proper voltage.) The Main Injector has been designed to hold six booster batches, but most likely it will only hold five due to kicker rise time limitations.

Both slow and fast cycling Boosters were considered. The slow cycling machine would have had the advantage of being able to fill the Main Ring rather quickly. However, this would have required a multiple turn extraction from the Booster, introducing the possibility of intensity modulation, besides the problems involved with designing the more complicated extraction system. Also, the Booster would then have had to accelerate beam with the same maximum charge as the original Main Ring, and this probably would not have been possible due to space charge effects (which get worse as the intensity increases) in the smaller machine. It was decided, for these reasons, to build a rapid cycling machine of fractional Main Ring radius.



Even with the general specifications decided upon, there were still a number of details to that needed to be worked out, like finalizing the basic lattice, and the requirements of the correction magnets. Injection and extraction systems were created, as well as the RF acceleration system. The gradient magnets were designed with consideration to the power supply system and vacuum chamber requirements. Construction progressed quickly and beam was first injected into the Booster in October 1970. The Main Ring received extracted beam the following spring.

Over the years, the original 16 RF cavities were increased to 18, then reduced to 17 when the LLRF room was expanded.

The Booster has typically operated well below its full capability during normal operations. This was due to the Main Ring aperture being only half the size of the Booster aperture. The LINAC upgrade, which took place in the summer of 1993, increased the energy of the LINAC beam to 400 MeV. The upgrade also increased the Booster aperture at injection due to adiabatic damping within the new LINAC, and the ability to produce larger antiproton stacks. But the Main Ring was not capable of accelerating the quantity of protons that could be provided. These mismatches between the Booster, the Antiproton Source, and Main Ring became acute.

The Main Injector removed these mismatches, and does the following:

1. Increases the number of protons targeted for Pbar production.
2. Increases the number of protons that can be delivered to the Tevatron.

The Main Injector and the Tevatron

Injection

The extraction of 400 MeV H^- ions from the LINAC begins after Klystron tank #7. This area is called the “400 MeV line. It is a transport line, similar in design to the Pbar AP-1 line. The line’s function is to transport beam from LINAC to the Booster, and to provide matching of each machine's lattice parameters. The line must also make a transition downward through a “chute to the Booster ring, which is about 15 feet below the LINAC. Injection into the Booster takes place at period 1.

The 400 MeV beam from LINAC can be directed into any one of three separate beamlines at the end of the LINAC enclosure. The beam pulses not deflected by the 400 MeV “chopper (B:CHOP) enter one of the two dump lines. If the 40° “spectrometer” magnet is powered, which is the normal mode of operation, beam is deflected into beam dump #2. A wire scanner probe at the end of the dump #2 line generates a momentum profile. The profile measures the average momentum and momentum spread of the beam from LINAC. If the spectrometer magnet is off then beam continues straight ahead to dump #1 (often called the “straight-ahead” dump). This dump line has diagnostics for measuring the transverse emittance of the LINAC beam and is normally used only for studies. The third line is the 400 MeV transport line, and delivers a selected part of the LINAC beam pulse to Booster.

The chopper just downstream of Klystron tank 7 determines the portion of the LINAC beam pulse sent to Booster. The chopper is a pulsed electrostatic deflector made up of a pair of charged plates. The length of the chopper pulse depends upon the requested beam intensity for Booster. The chopper timing is adjusted to select the best portion of the LINAC pulse. The chopper plates are charged up ~60 kV between LINAC pulses. Initially, the plates are at the same potential so no deflection occurs to the leading edge of the LINAC pulse. At Chop time on (B:CTCBxx), the "On" plate is crowbared, deflecting beam upwards. At the end of the pulse (Chop time end B:CTCExx), the "Off" plate is discharged, sending the remainder of the LINAC pulse straight ahead to the dump. The upward kick delivered by the chopper sends beam off-center through a focusing quadrupole (B:Q2) which in turn delivers an additional upward bend (figure 1.1). Beam that has been deflected by the chopper and quad passes through the field region of the Lambertson (B:LAM), which delivers the first horizontal bend to the extracted beam, a 10.96° bend to the West.

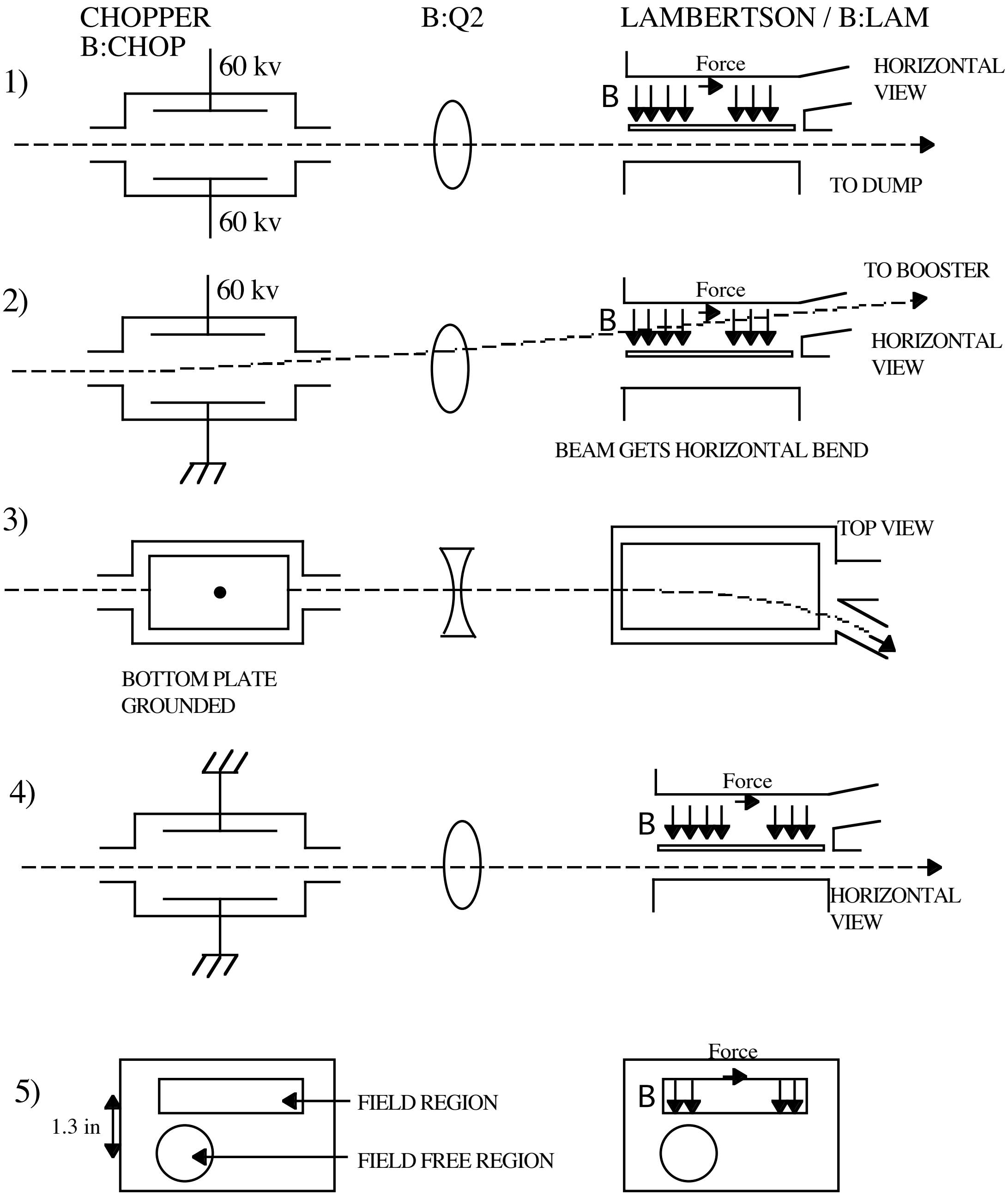


figure 1.1

A vertical trim magnet, MV0, follows the Lambertson (a Pbar Debuncher style trim). MV0 removes the vertical angle caused by the chopper and quadrupole combination. After MV0, the beam experiences another horizontal bend by MH1, which bends beam another 4.82° to the West. The final bending element before the chute is MV1 which deflects beam 12.51° downwards, somewhat less than the actual 13° angle of the chute. In the Booster enclosure, after the chute, another vertical bend, MV2, straightens out the beam trajectory at the level of the Booster ring.

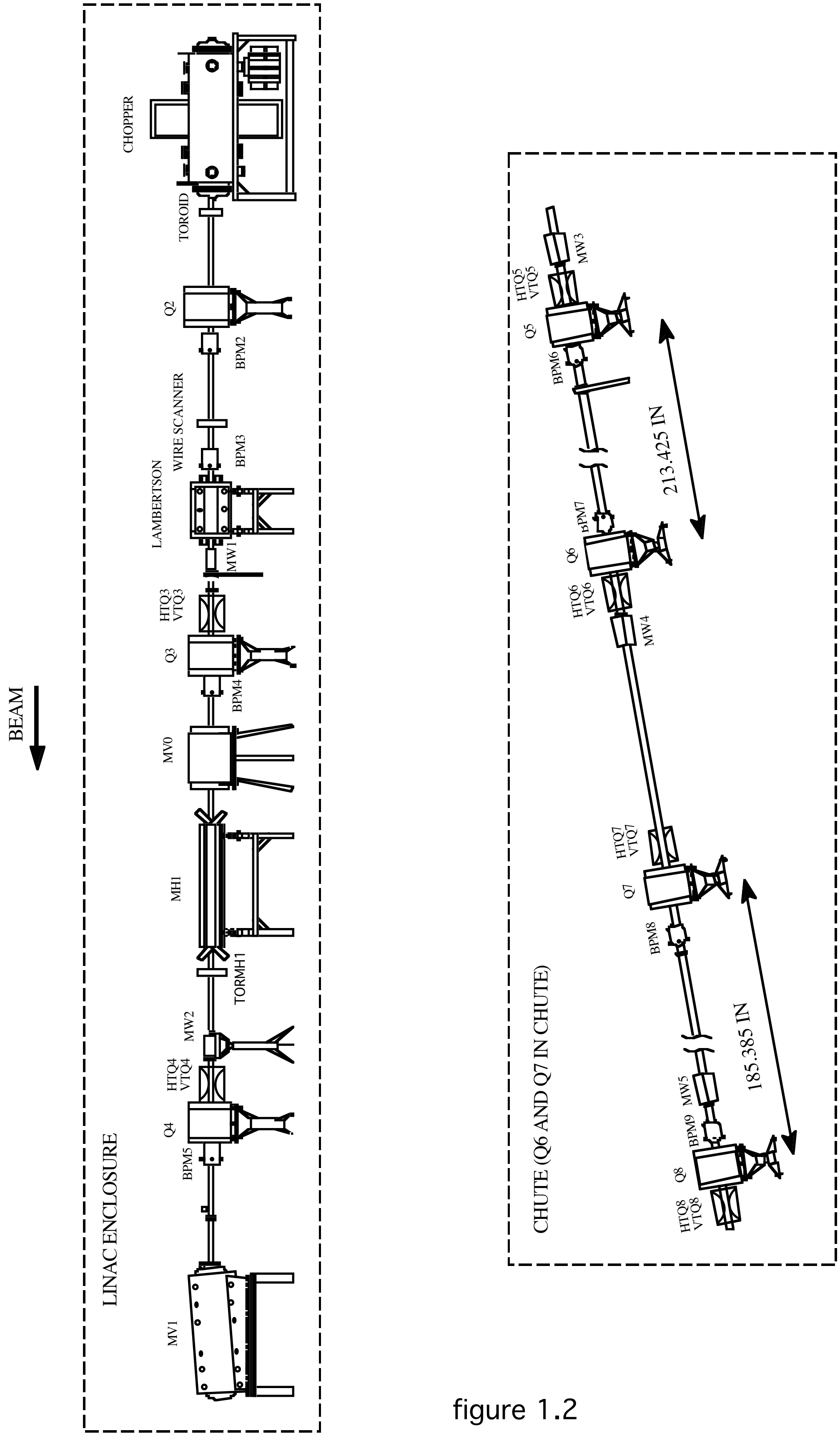

BEAM
LINAC ENCLOSURE
CHOPPER
TOROID
Q2
BPM2
WIRE SCANNER
BPM3
LAMBERTSON
MW1
HTQ3
VTQ3
Q3
BPM4
MV0
MH1
TORMH1
MW2
HTQ4
VTQ4
Q4
BPM5
MV1
CHUTE (Q6 AND Q7 IN CHUTE)
MW3
HTQ5
VTQ5
Q5
BPM6
213.425 IN
BPM7
Q6
HTQ6
VTQ6
MW4
HTQ7
VTQ7
Q7
BPM8
185.385 IN
MW5
BPM9
Q8
HTQ8
VTQ8

figure 1.2

The vertical dogleg required to transport beam through the chute introduces a vertical dispersion that must be dealt with before injection into the Booster. If unchecked, the dispersion would cause the beam's vertical emittance to be larger. The quadrupoles in the chute between MV1 and MV2 (B:Q5–B:Q8) have been arranged to cancel the vertical dispersion before the beam exits MV2. The Booster synchrotron has no major vertical bending magnets (only trims) and therefore has no intrinsic vertical dispersion. It was important to design a line that introduced no vertical dispersion to the Booster. (See figure 1.2)

The final section of the 400 MeV line is the matching section. In the first portion of the matching section the transverse phase ellipse of the beam is rotated to achieve efficient injection. Seven quadrupoles are used in the matching section to generate a FDFFFDD configuration. In practice, only five quadrupoles are needed to generate the required lattice match, but the present set-up allows for greater flexibility (see figure 1.3). The quads used in the 400 MeV line are of two types, the Loma Linda style quads (B:Q2, B:Q5-8 and B:Q13) and the old 200 MeV style quads (all others).

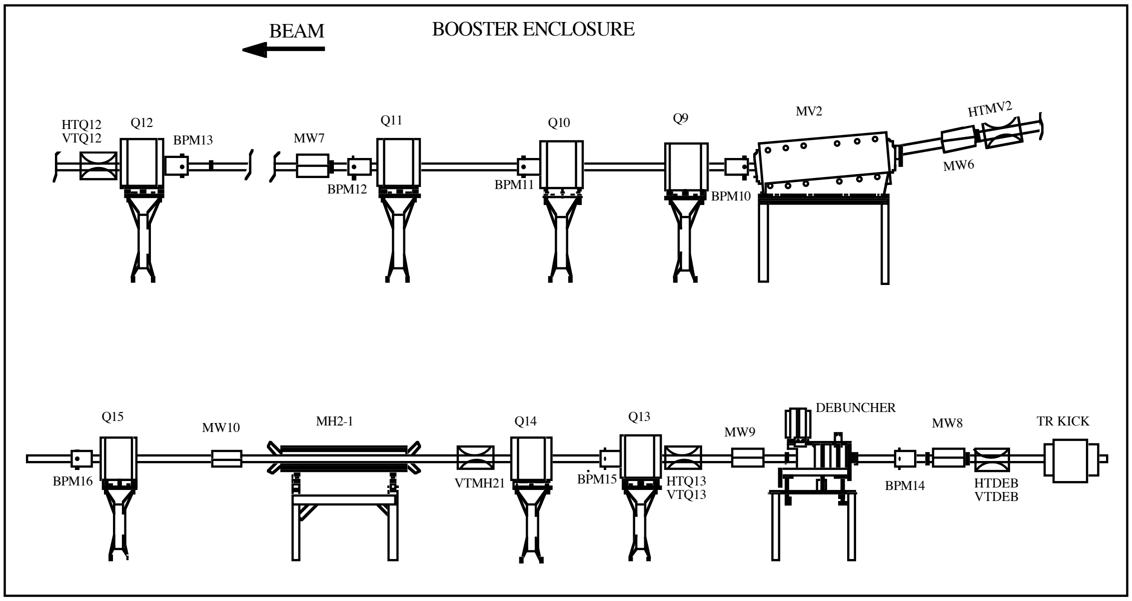


figure 1.3

Also located in the phase matching section is the "Debuncher." The Debuncher is a Klystron cavity similar to one of the cavities found in the transition section of LINAC. Its purpose is to reduce the momentum spread of the beam and remove the 805 MHz RF structure from LINAC. After the Debuncher, there is a set of three dipoles collectively called MH2 that bends the beam 28.6° horizontally towards the Booster and into the field region of the injection septum. The dipoles are reworked "Cooling Ring" dipoles (a decommissioned ring used for beam cooling studies) that are powered in series. These three dipole magnets replace the single MH2 magnet used in the old 200 MeV line that provided a 26° bend.

Before injection, the lattice of the 400 MeV line must be matched to that of the Booster. The lattice match, the second part of the matching section, is accomplished by using the last two quadrupoles in the 400 MeV line, B:Q16 and B:Q17. These quads duplicate the upstream lattice of Long 1 (see figure 1.4). Q16 and Q17, which are F and D quadrupoles respectively, align with those of the combined function magnets just upstream of injection. Their field strengths are also equal to those found in their respective combined function magnets. 16 trim dipoles steer beam along the 400 MeV line. The trims are sometimes configured in packages, as in the Booster ring, with a horizontal trim nested inside a vertical trim. Trims at the end of the 400 MeV line are also used to fine tune the position and angle of the beam entering the injection girder.

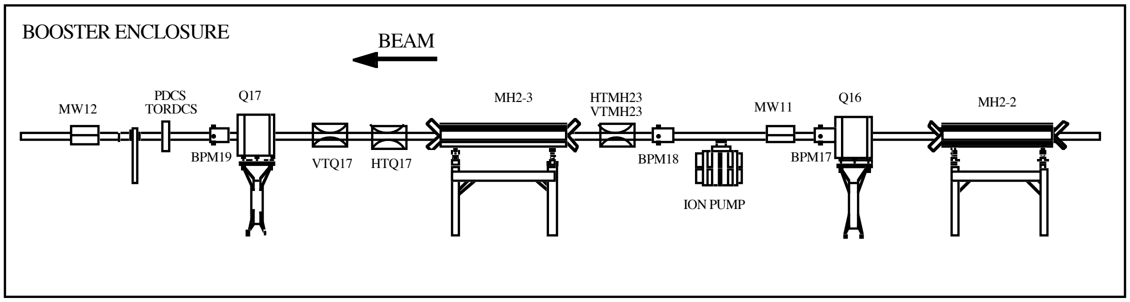


figure 1.4

The 400 MeV line intersects the Booster ring at the injection girder, where a DC septum magnet (B:DCSEP) removes the horizontal bend angle created by MH2 (figure 1.5). Beam is then put on a trajectory parallel to the Booster closed-orbit, about 8 cm. radially to the outside. Circulating beam passes through the field-free region of the septum magnet and isn't deflected. Both injected and circulating beams pass through the upstream "Orbump" magnet. This magnet (really two dipoles connected in a "dogleg" configuration) bends the circulating beam outward and the injected beam inward so that they overlap. Remember that the injected and circulating beams are of opposite polarity; the circulating beam is made up of protons, while the injected beam is still H^- ions. The injection trajectory centers the beam on a stripping foil located between the second and third Orbump magnets. The H^- ions and circulating beam passes through the stripping foil, which removes the electrons from most of the H^- ions and yields protons. The "electron catcher" captures the stripped electrons. The two downstream Orbump magnets then bends the proton beam radially inwards, into the closed orbit. The remaining unstripped H^- ions are bent outward and hit the "H^- detector." The Orbump magnets are pulsed for ~50 msec at the beginning of the Booster cycle. After the supply turns off, circulating beam is no longer bumped outward through the stripping foil; this minimizes beam loss and scattering caused by the foil.

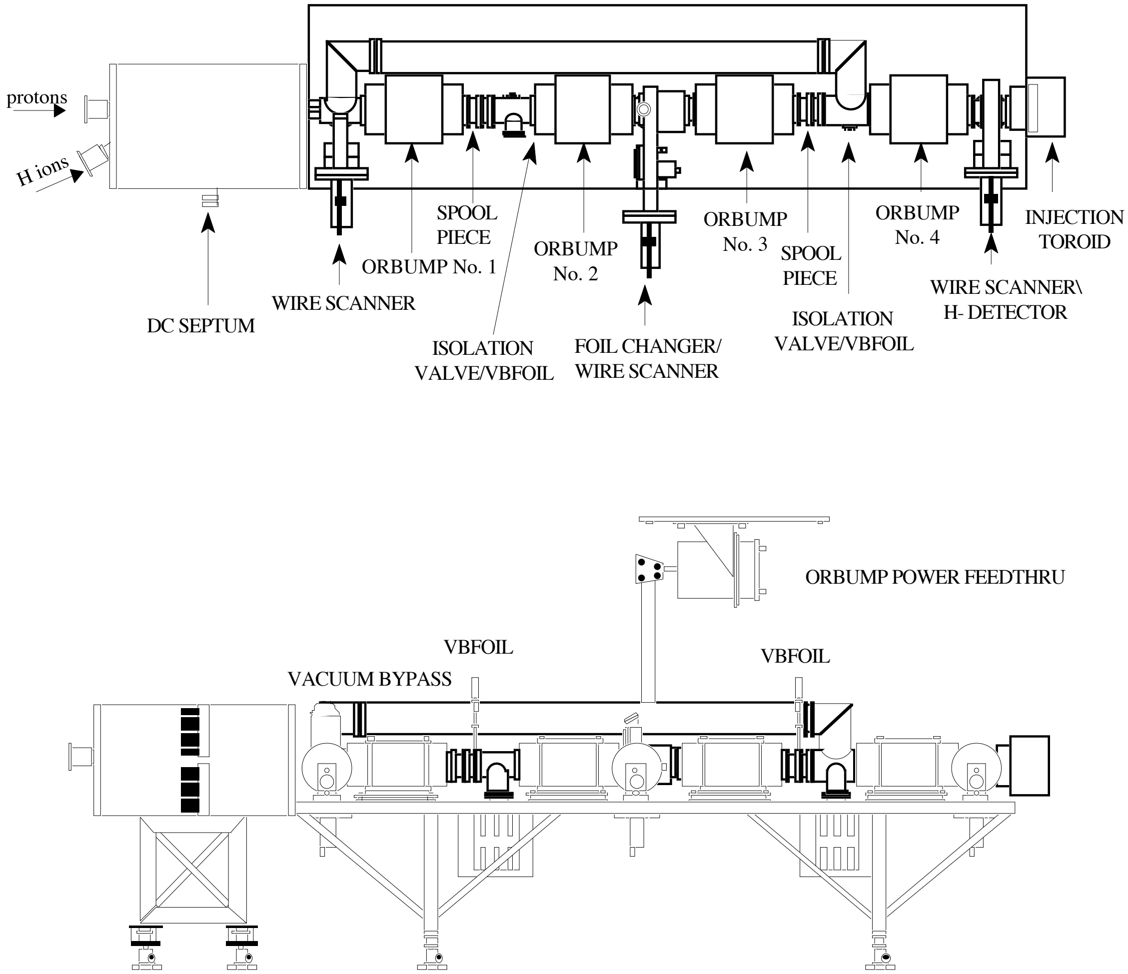
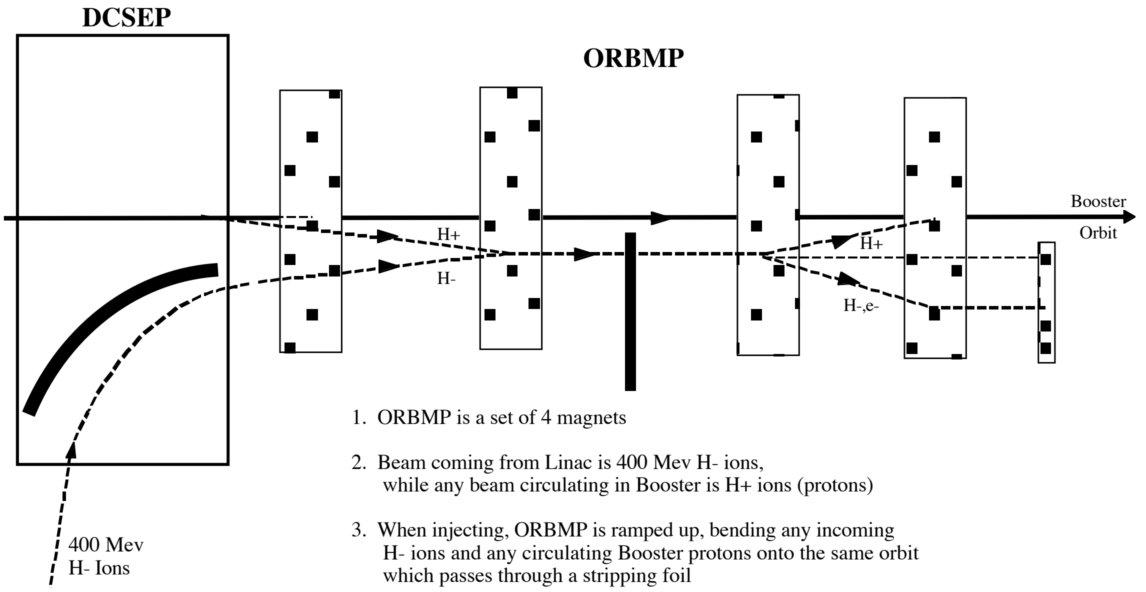


figure 1.5

The stripping foil used in removing the two electrons from the H^- ions is made of a thin layer of carbon. There are actually 8 foils contained in the injection girder that can be rotated into place if necessary. The changer motor is an AC motor identical to those used on the Multiwires. There are two windows provided on the girder to view the condition of the foils and their position. One window has a view of the foil in the beam trajectory and can be seen only if an operator climbs on top of the ORBUMP. Figure 1.6 shows the ORBUMP and other equipment used at the Long 1 Injection.

Long 1 Injection



1. ORBMP is a set of 4 magnets
2. Beam coming from Linac is 400 Mev H- ions, while any beam circulating in Booster is H+ ions (protons)
3. When injecting, ORBMP is ramped up, bending any incoming H- ions and any circulating Booster protons onto the same orbit which passes through a stripping foil
4. The foil strips some of the electrons off of the H- ions, making protons
5. Once beam is injected, ORBMP is ramped back down so that the circulating Booster beam does not continue to go through the stripping foil

figure 1.6

The Booster uses a loading scheme that overlays injected beam with circulating beam that increases beam intensity from the Booster. The original proton ion source produced more beam current than the present H^- source, but was limited to injection over a single Booster "turn." In the original scheme, the only way to control LINAC beam intensity was by purposely misphasing the Buncher. With the present method of injection, it is easier to control the beam intensity out of LINAC.

The revolution period in Booster at injection is 2.22 µsec, while the pulse width in LINAC is approximately 40 µsec long. The 400 MeV chopper selects only a portion of the LINAC beam; the remainder of the beam is sent to one of the LINAC dumps. Extending the chop width generates multiple Booster turns. Although the LINAC beam pulse is long enough to run about 18 turns (18 turns would be a 39.96 µsec chop width selected from the 40 µsec LINAC pulse). Operationally, the practical limit for maximum intensity is 5 or 6 turns. Normally, fractional turns are not used—this should be distinguished from the ability of running partial batches to the Main Injector, which is accomplished during the extraction process.

Diagnostics in the 400 MeV line include nineteen Beam Position Monitors (BPM's), twelve multiwires, three toroids, and Beam Loss Monitors (BLM's). The old 200 MeV line did not have a BPM system. It relied solely upon multiwires for position monitoring. BPM's have the advantage of being passive and not interfering with the beam. Although multiwires do cause some beam loss and emittance growth, they have the advantage of displaying a beam profile.

The 400 MeV line BPM system operates at 201 MHz, unlike the system used in the Booster ring. (The Klystron cavities operate at 805 MHz, with beam occupying every forth bucket.) BPM's at the end of the line and around the injection girder can be used for steering the beam. The BPM's on either end of the injection girder have their signals split. One signal is used for measuring the beam position during the first several turns when there is enough remaining 201 MHz RF structure to produce a usable signal. The other signal monitors for normal position after Booster RF bunches the beam.

Toroids measure the beam current and from this measurement they derive beam intensity. When properly calibrated, the toroids can help locate where beam is lost. But since the 400 MeV upgrade, not all of the toroids are hooked up. Toroids are located after MH1 (B:TORMH1) and upstream of B:DCSEP (B:TORDCS). The BLM's used in the 200 MeV line were not very useful because of the high losses due to the large emittance beam. However, in the 400 MeV line, BLM's are a useful diagnostic for startup tuning and for locating restrictions. It should be remembered that BLM's downstream of the chute will also show losses from circulating beam in Booster. The injection girder itself has all of the diagnostic tools of the 400 MeV line, but because of the circulating beam, caution must be used with any of the three wire scanners. Figure 1.7 shows the locations of the diagnostics in the girder section.

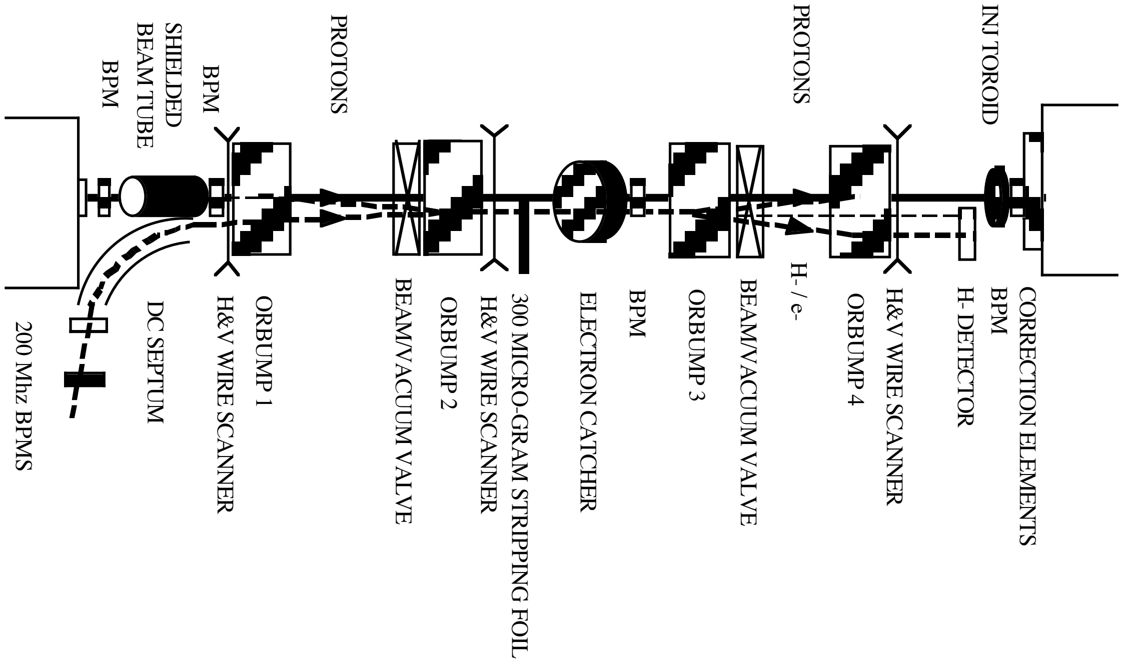


figure 1.7

Gradient Magnets and Power Supplies

Lattice

In most circular accelerators the beam is subjected to a repetitive pattern of focusing (quadrupole) fields; this repeating pattern is called the machine “lattice” and, in the Booster, the repetitive elements of the pattern are called “periods.” The Booster lattice consists of 24 identical periods, each containing two horizontally focusing magnets (F magnet) and two horizontally defocusing magnets (D magnet), along with a 6 meter “long straight” section and a 1.2 meter “short straight” section (see figure 2.1a). This type of lattice is schematically expressed by FOFDOOD. This represents a focusing magnet (F), a short drift space (O), another focusing magnet (F), a defocusing magnet (D), a long drift space (OO), and another defocusing magnet (D). (DOODFOF would also be correct). There are many other conceivable lattices; for instance, Main Injector uses a FODO lattice.

Magnets are placed on girders and are part of a module which consists of one D and one F magnet, a choke, a capacitor bank, a correction element package, a beam position detector, and an ion pump (see figures 2.1b and 2.1c). Two magnet girders form one period of the Booster lattice, so there are 48 modules in the ring.

The long straights are used for injection and extraction areas, RF acceleration cavities, and special correction magnets and beam diagnostics (see the appendix at the end of this chapter). Numbering of the lattice periods arbitrarily begins at the injection long straight, designated as “long 1.” The long straights precede the correspondingly numbered short straights, so the short straight immediately downstream of long 1 is labeled “short 1.” Incidentally, the terms “upstream” and “downstream” refer to the direction of beam motion. Beam always travels from upstream to downstream. There are 24 long and 24 short straight sections in Booster for a total of 96 gradient magnets in the ring. As mentioned in the introduction, the standard cell length is 19.76 meters.

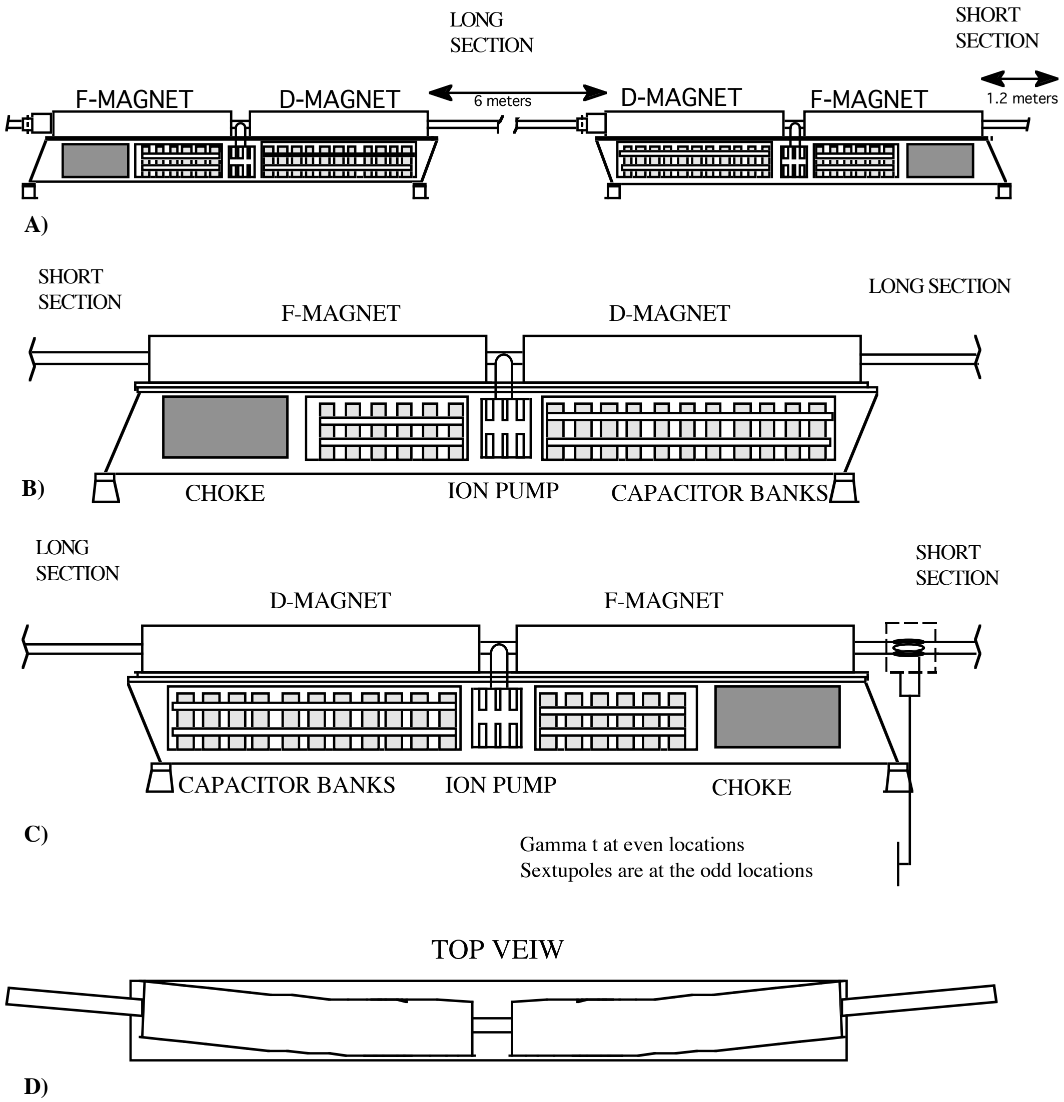
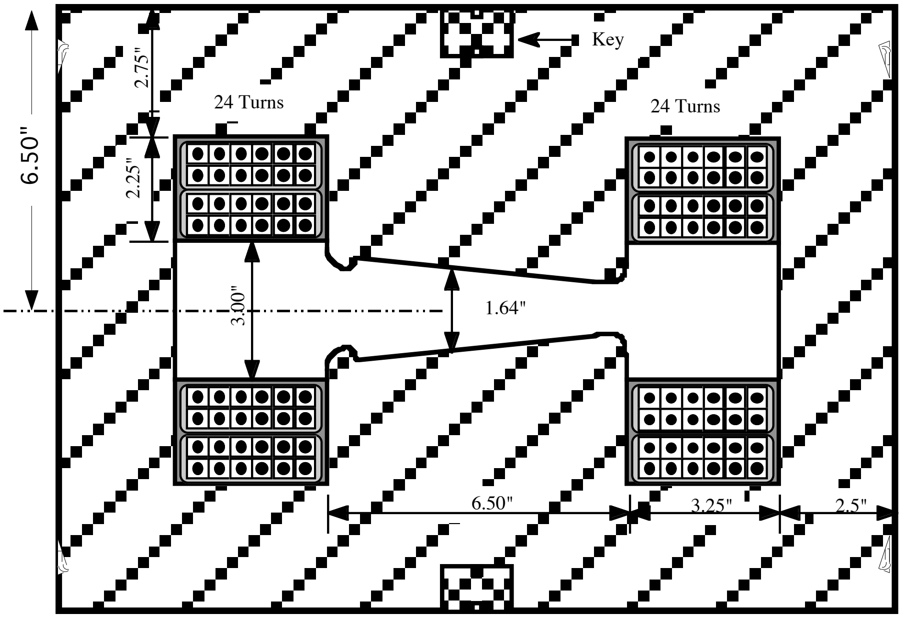


Figure 2.1

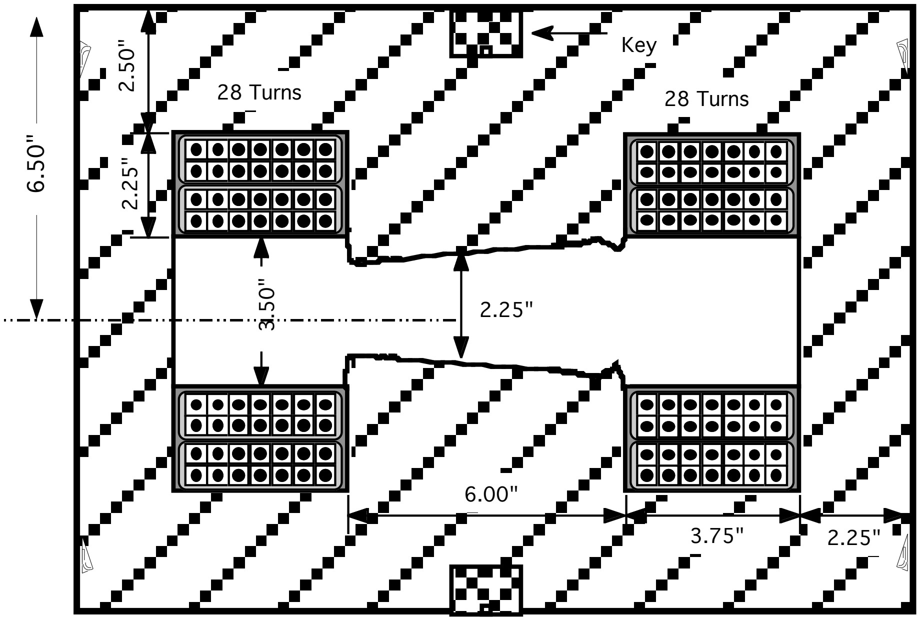
A) Typical lattice cell starting witha focusing magnet and ending witha short straight section (FDOODFO).
B) Upstream section of the cell showing girder elements.
C) Downstream section of Cell.
D) Top view showing relative curvature.

Magnets

Booster magnets, in contrast to those in the Main Injector, are “combined function” Magnets. Each magnet bends the beam (a dipole magnet function) and focuses the beam either horizontally or vertically (a quadrupole function). Figure 2.2.1 shows a cross sectional view of a focusing and defocusing magnet. The F and D magnets have apertures that accommodate the beam size at their respective positions in the lattice.



Focusing Magnet



Defocusing Magnet

figure 2.2.1

For the F magnets, the horizontal aperture (good field) width is 4.3 inches and the vertical aperture is 1.64 inches. The corresponding measurements in a D magnet are 3.0 inches and 2.25 inches (see the device appendix at the end of this section). Please note that these measurements are taken at the center of the pole tip. Figures 2.2.2 and 2.2.3 shows that the field vector axis for each magnet is a dipole effect while the off axis is like a quadrupole effect.

Focusing Magnet

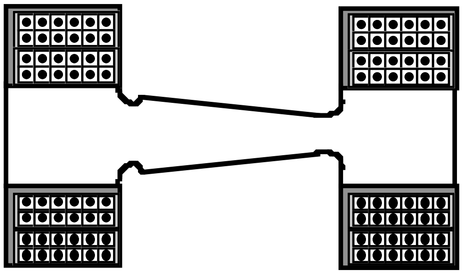
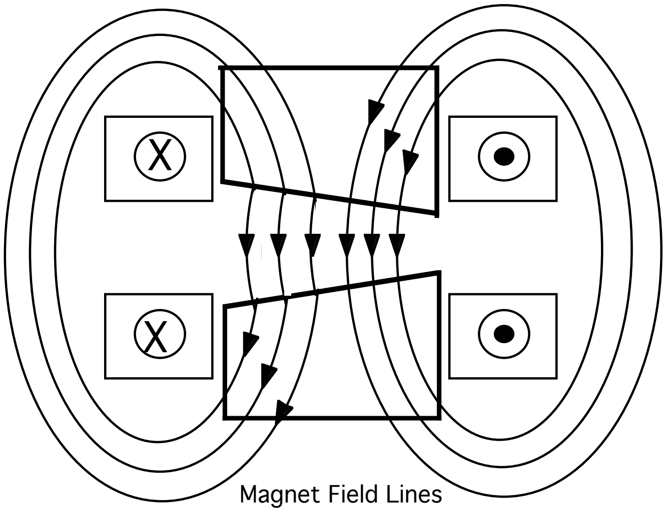
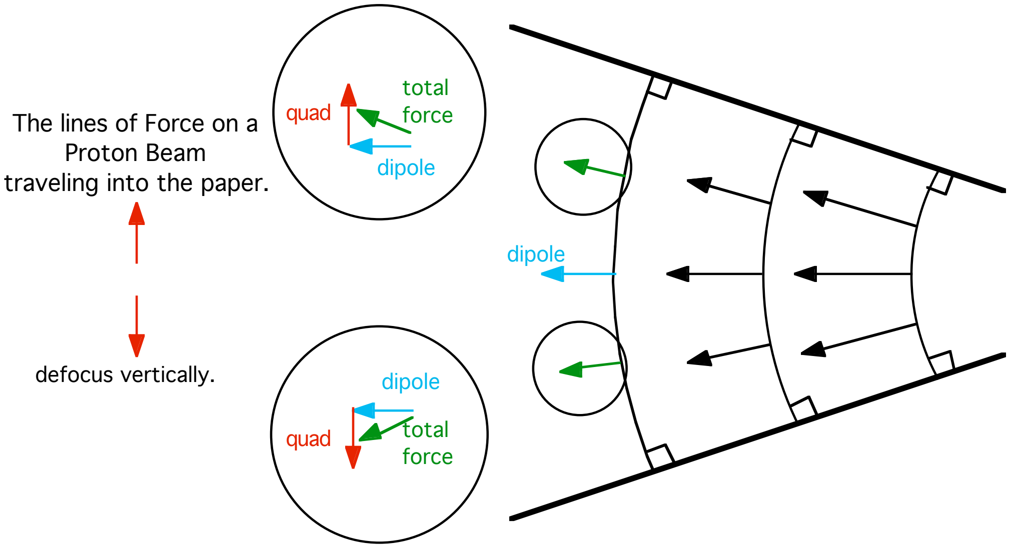


figure 2.2.2



Magnet Field Lines
(induced by current flowing through the coils)



The lines of Force on a Proton Beam traveling into the paper.

defocus vertically.

Defocusing Magnet

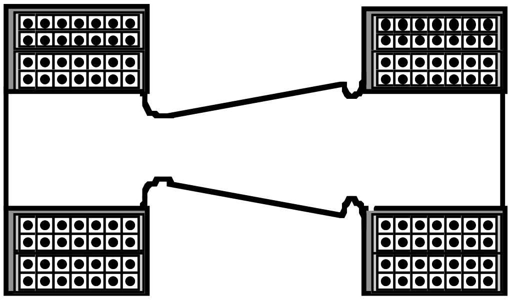
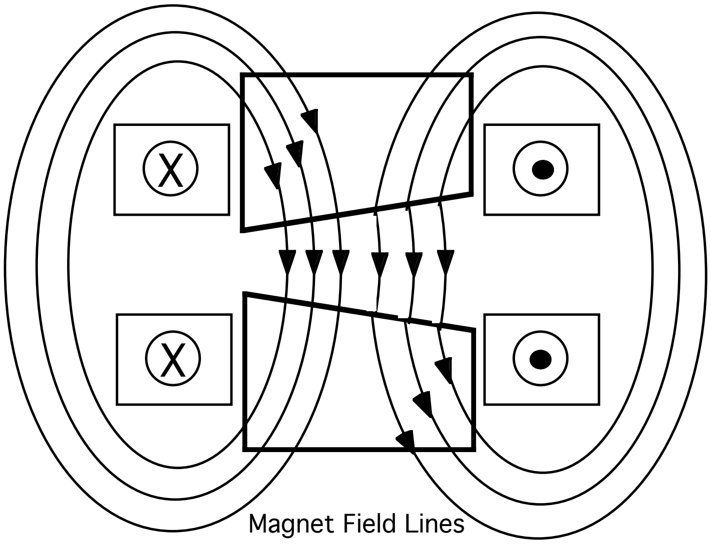


figure 2.2.3



Magnet Field Lines
(induced by current flowing through the coils)

The lines of Force on a
Proton Beam
traveling into the paper.

focus vertically.

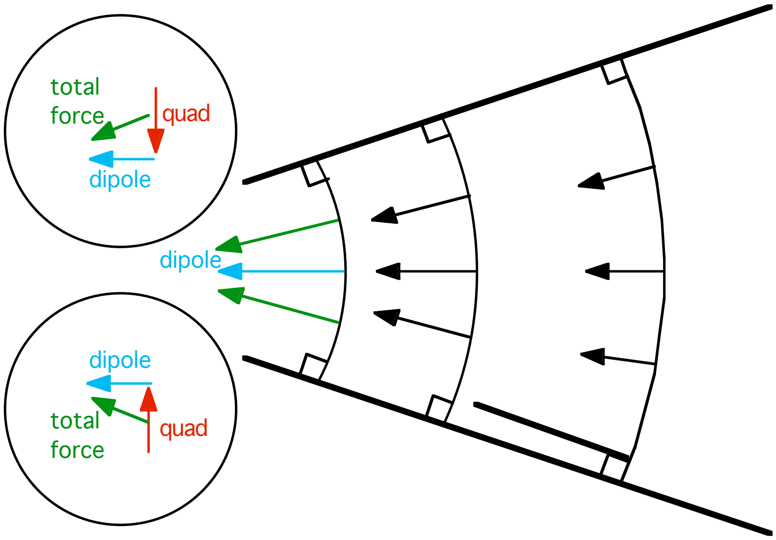
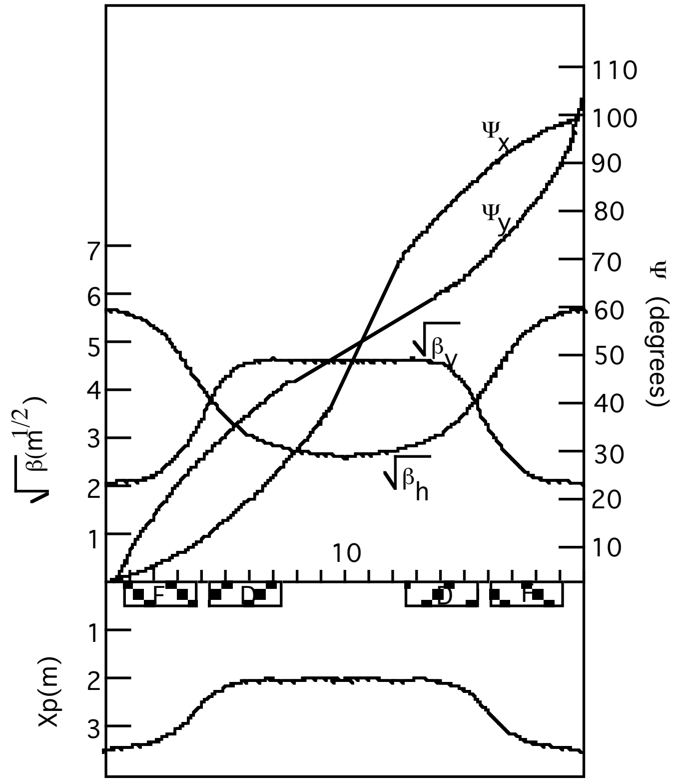


Figure 2.3 shows the horizontal dispersion and beta functions across a Booster period—these both relate to the cross section of the beam (see the *Concepts Rookie Book*). It shows the correspondence between D & F magnets and 'Beta v' & 'Beta h.' (Beta's will not be discussed here but can be thought of in terms of transverse beam size.) Also shown is the phase advance, which is simply how far through a betatron oscillation the beam has gone (360° would be a complete oscillation).



Booster lattice
figure 2.3

The magnets are built by stacking some 4400 silicon steel laminations (0.025″ thick) together and bonding them with epoxy resin, which is heat cured in several stages. These are "canned" magnets, which means the laminations are inside the vacuum container. The container in this case is made of thin, stainless steel sheets welded to the outside of the laminations. (Laminations are used to minimize eddy currents in the magnets.) The laminations are stacked in such a way that magnets have the curvature of the beam path. Also, end laminations are tapered to create a small sextupole field component that reduces the chromaticity. This contour of pole tips improves the field quality near the edges of the magnets pole faces. The completed magnet has a cross section of 13 inches by 18 inches and is 10 feet long. The magnet assembly weighs approximately 5 tons.

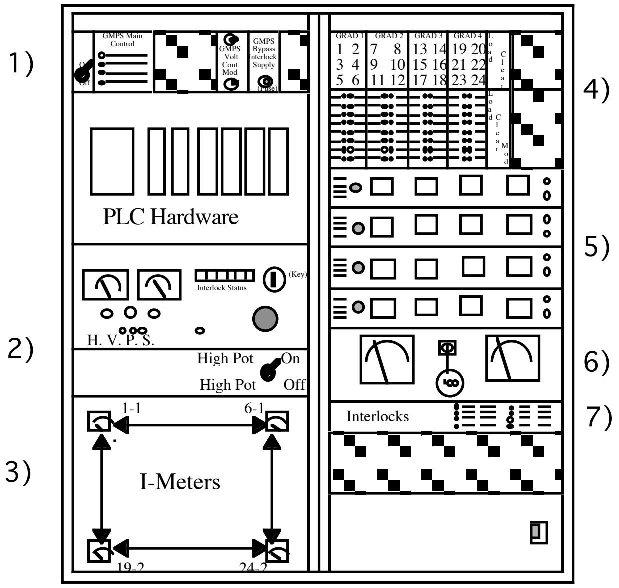
The magnet coils are in the form of flat "pancakes," with two coils located above the mid plane of the magnet and two located below. The conductor is 0.46″ square copper with a hole through the center for

LCW (Low Conductivity Water) to dissipate the heat. The F magnets have 12 turns per pancake while the D's have 14 turns.

GMPS

Power for the Booster magnets is supplied by the Gradient Magnet Power Supply (GMPS). GMPS is really made up of four programmed, solid-state power supplies. The Booster magnet electrical circuit consists of 48 resonant cells connected in series. Each cell consists of one F and one D magnet, a choke, and a capacitor bank. The four GMPS power supplies are all in series with the magnet circuit, one supply for twelve cells. There are two supplies in the west transformer yard, and two in the east transformer yard, all operating directly off the 13.8 kV line. The monitoring and control of the essential GMPS parameters can be found in the Booster west gallery at the GMPS racks. (See figure 2.4)

GMPS Racks



1) GMPS Main Control Module
2) Hi-pot power supply
3) Choke imbalance current readbacks
4) (4) load quadrant modules
   (1) load clear module
5) Brentford voltage/current readbacks
6) Ground fault detector
7) Tunnel period interlock trip status module

figure 2.4

The magnetic field in the Booster magnets is of the form:

$$B = B_{dc} - B_{ac} \cos 2\pi ft$$

which means the power supplies must generate a current (ignoring saturation effects in the magnets) of the form:

$$I = I_{dc} - I_{ac} \cos 2\pi ft$$

Most previous rapid-cycling machines generated the DC and AC components separately. In the Booster it was decided, for reasons of economy, to generate both simultaneously through the use of Silicon

Controlled Rectifier (SCR) supplies. The magnet circuit is “resonant” that is, energy is exchanged between the magnets and the capacitor banks with the power supply making up the losses. A distributed choke system bypasses the DC current around the capacitors and provides coupling between the different resonant cells. (See figure 2.5)

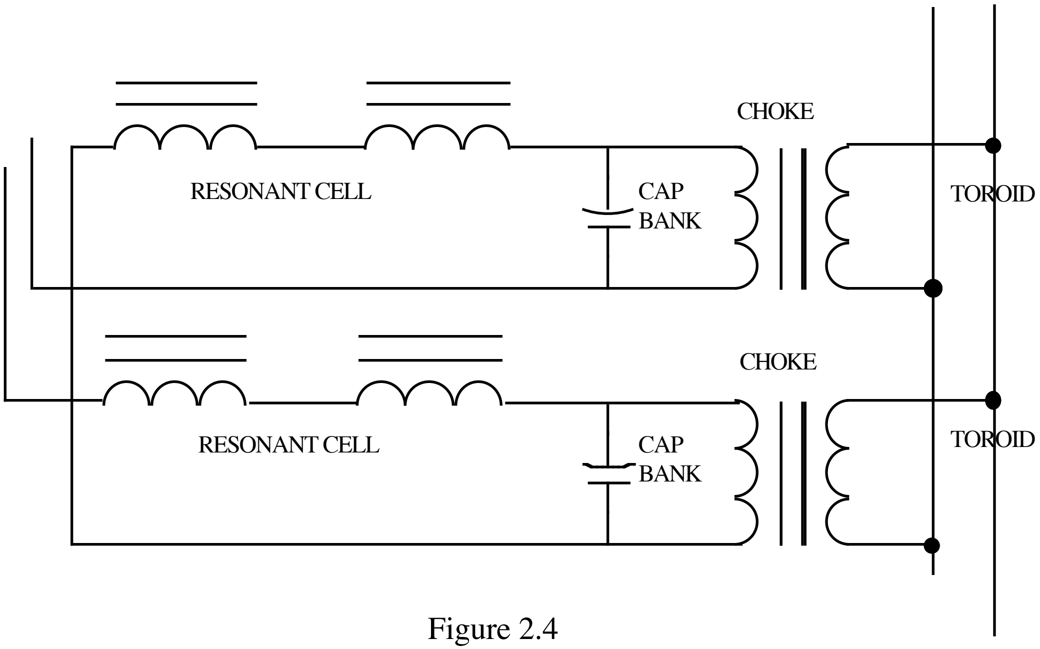


Figure 2.4
Resonant Cell

The operating frequency of the power supply system was studied at 30, 15 and 7$^1/_2$ Hz, with 15 Hz being the final choice (again for economic reasons). Each resonant cell has a trimmer capacitor with taps at $^1/_8$, $^1/_8$, $^1/_4$, and $^1/_2$ (yes, there are two $^1/_8$ taps) of the normal capacitance value which is used to tune each cell independently for exactly 15 Hz.

The power supplies are 12 phase supplies with a basic ripple frequency of 720 Hz (12 phases at 60 Hz). Each supply consists of two 3-phase SCR bridges connected in series. Each 13.8 kV transformer has two secondary windings supplying voltage to the two bridge circuits displaced in phase by ±30˚ (this is a special transformer type known as a “zigzag”). An L-C filter network on the output of each supply further reduces the output ripple. Firing circuits control the firing angle of the SCRs so that the output voltage is proportional to the signal provided by a magnet regulator. The regulator output is a 15 Hz biased trapezoidal wave synchronized to the 60 Hz line frequency.

A special magnet located in the west equipment gallery monitors the magnetic field of the gradient magnets. The coil of this “reference magnet” connects in series with the ring magnets. This means the reference magnet’s field tracks the magnetic field in the ring. A coil located in the gap of the reference magnet detects the rate of change of the magnetic field, B-dot. This provides timing information used to sample the magnet current transductor signal at its maximum and minimum. The requested maximum and minimum values of the magnet current are set via the control system (B:IMAX and B:IMIN, respectively). Switching between these two levels generates a 15 Hz square-wave that is filtered to produce the biased trapezoidal wave input to the SCR firing circuits.

Figure 2.6 is a simplified block diagram of GMPS and its feedback pathways. Although not shown directly, there are actually two feedback paths. The voltage feedback is done at each individual power supply. The GMPS system design allows Booster operation with just 3 of the 4 supplies.

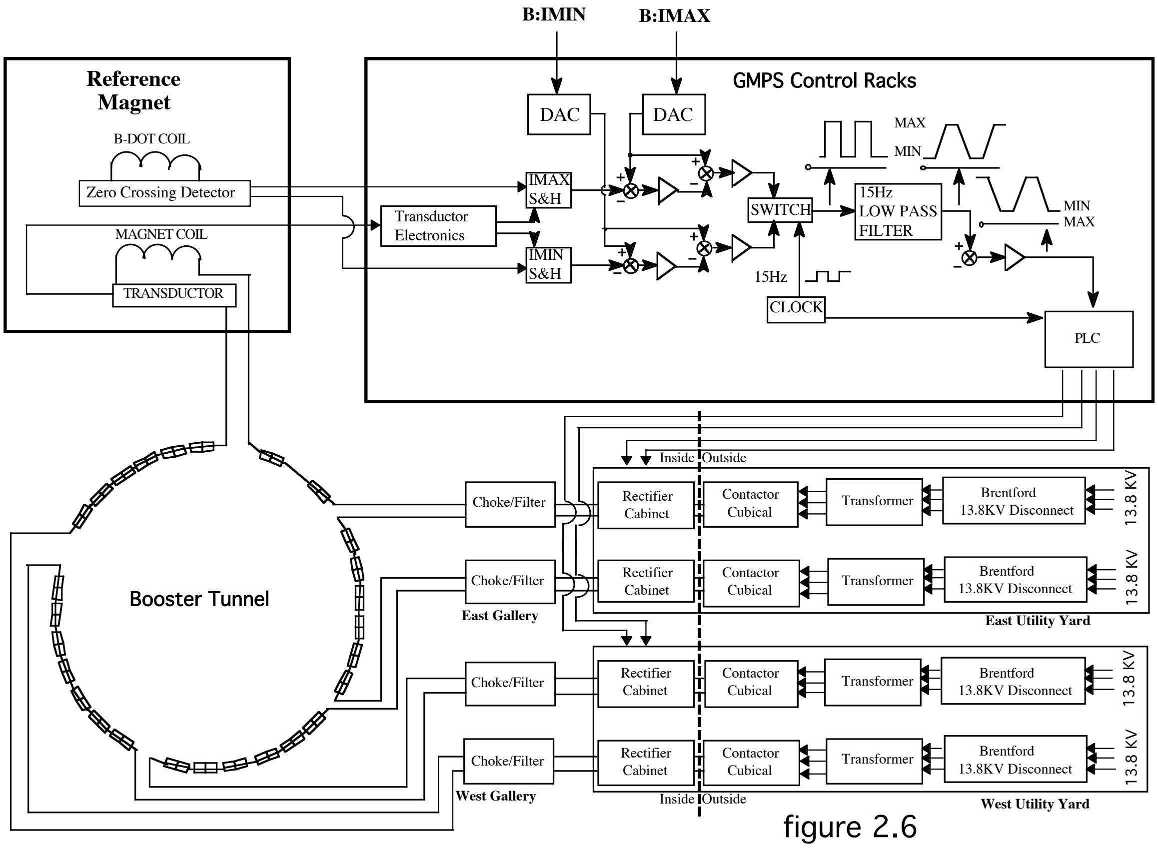

Gradient Magnet Power Supply System

figure 2.6

The B-dot signal from the reference magnet is processed to generate a 15 Hz TTL signal that is sent to the MAC room. The Time Line Generator (TLG) uses this information to synchronize the Booster clock events and LINAC timing. When GMPS is off, the TLG uses a backup 15 Hz clock signal from a line-locked source in the MAC room. Once GMPS is turned back on there is a delay of about 11 seconds to allow the GMPS output to stabilize before the 15 Hz signal is again transmitted to the MAC room. There is a second back-up 15 Hz clock in the Pre-Acc area which is used only when both GMPS and the MAC room 15 Hz clocks go down. Adjusting the parameter B:RSTDLY allows precise tuning of the TLG event generation, so that beam injection will occur when B-dot is zero (or wherever desired). (See figure 2.7a & b)

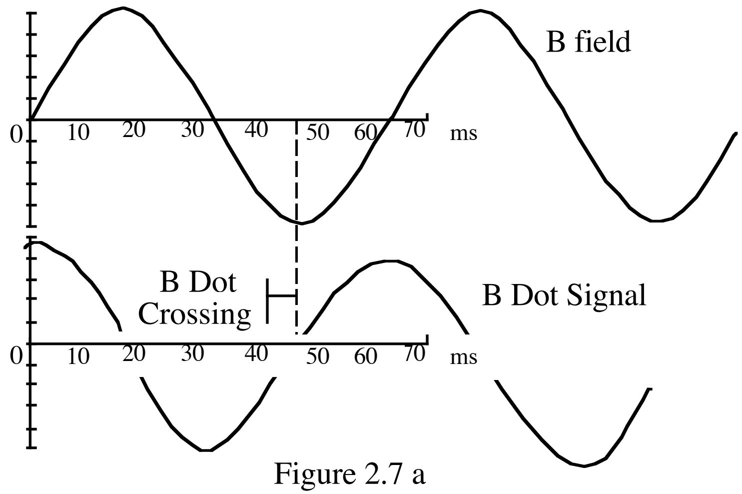


Figure 2.7 a
Booster B-dot crossing

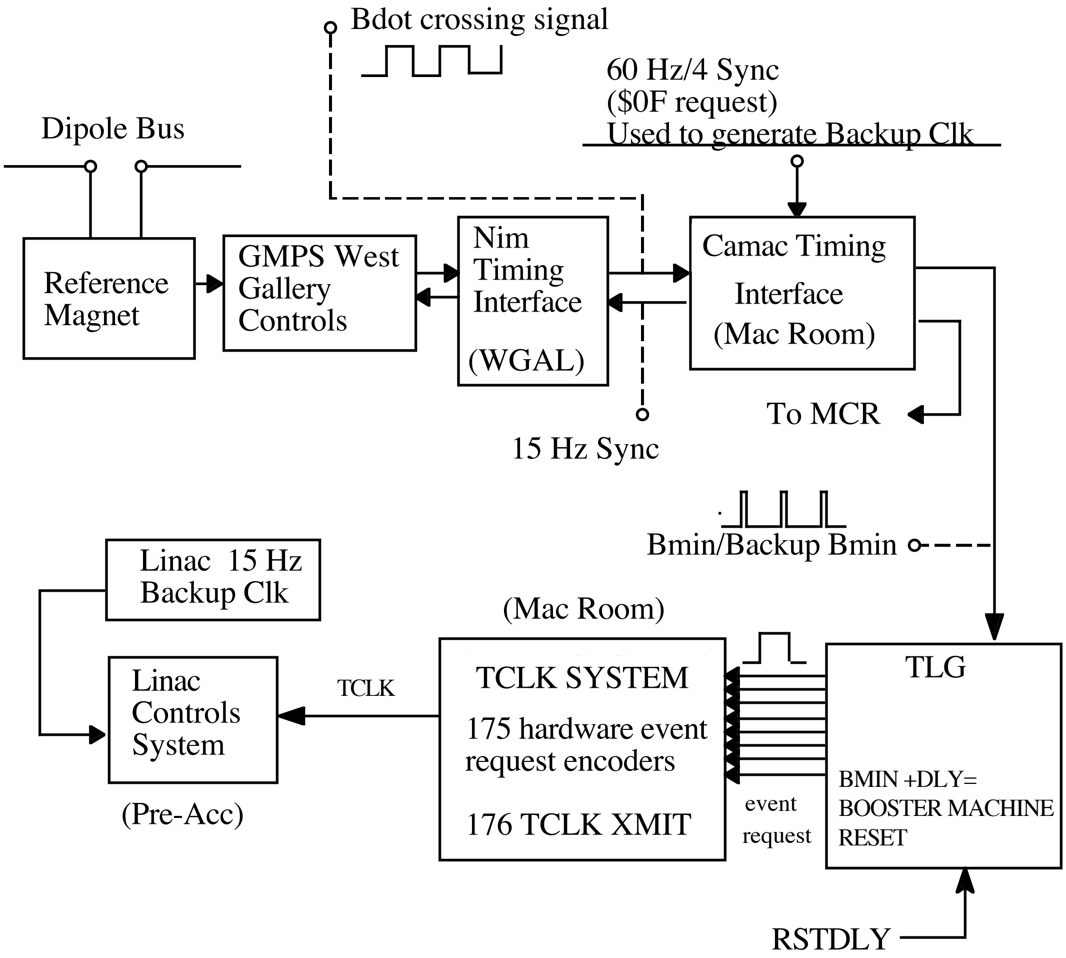


Figure 2.7 b
Booster Clock Synchronization

RF

The application of RF (Radio Frequency) energy accelerates the Booster beam. The beam receives this energy as it passes through each of the 17 ferrite-tuned resonators, commonly referred to as "cavities," located around the Booster ring. A 100 kW PA Power Amplifier) drives each cavity. A set of "low level" RF waveforms drives the "high level" RF which is made up of amplifiers, cavities, and associated hardware.

There are three distinct phases to the accelerating cycle:

1) Injection, capture, and bunching over the first 2 msec.
2) Acceleration, which lasts about 29 msec.
3) Phase locking to the Main Injector and extraction, which occurs over the final 2.5 msec. (If phase locking to the Main Injector is not desired, then the frequency trigger is withheld, and the acceleration sequence proceeds the rest of the way to extraction.)

During acceleration the RF frequency must follow the change in velocity in the protons; the frequency at injection is roughly 37.86 MHz and increases to 52.81 MHz at extraction time. The frequency of the RF system is the 84th harmonic of the revolution frequency of the Booster beam; the Booster is said to have a "harmonic number" of 84 (for comparison, Main Injector's harmonic number is 588). Hence, beam requires about 2.2 μsec to make one circuit of Booster at 400 MeV and only about 1.6 μsec at 8 GeV.

There are 84 stable phase space areas where beam may be captured and accelerated. These areas are called "buckets" A bucket may exist with or without beam. The beam captured within a bucket is referred to as a "bunch." Beam that has been captured by a series of RF buckets is said to be "bunched." An electronics card generates an approximate frequency program, containing up to 1,000 time-value pairs. Feedback loops make corrections to this program, which then keeps the beam at the correct position and dampens phase oscillations. As the RF frequency changes, the cavities are tuned to resonance by varying the current in bus bars, which link ferrite rings in the tuners.

RF acceleration in the Booster begins with the beam being adiabatically captured. This capture is accomplished by letting the LINAC beam "debunch" (that is, lose its RF structure) and then circulate in the ring without acceleration. The Debuncher cavity in the 400 MeV line reduces the momentum spread of the injected beam by decelerating the early arriving particles and accelerating the late arriving particles. (One can also change the average momentum of the injected beam by changing the phase of the Debuncher.) The Debuncher could be called a Buncher since it reduces the longitudinal beam growth. The ~0.3% energy spread of LINAC beam would make transfer inefficient without the Debuncher. Most of the ~ 801 MHz structure on the beam has been lost after about 5 to 10 revolutions around the Booster. After all the injected beam is circulating, adjacent stations are brought into phase over a period of 200-300 nanoseconds; this process is called “paraphasing.”

Booster RF stations are divided into two groups, “A” and “B.” The “A” and “B” refer to the vector phase relationships. (Actually, voltage is applied to the gaps in the RF cavities, but the vector sum of group A and B stations are electrically 180 degrees out of phase. When the vector sum of the RF is zero, no net acceleration or bunching occurs.)

As the phase difference between the A and B stations is removed, particles are captured into 37.7 MHz buckets. Shifting the RF phase relative to the beam with the phase shifter driver then accelerates the beam. The basic acceleration process is to increase the RF in conjunction with the ramping dipole magnets using beam feedback to maintain stability. (We will discuss the details of this in the next section.) The acceleration process lasts for approximately 33 msec. At the end of this time, beam has reached an energy of 8 GeV and is ready for transfer to the Main Injector.

A stable and consistent RF frequency is needed at injection, when beam is captured and bunched. The direct digital synthesizer (DDS), which replaced the voltage-controlled oscillator (VCO), operates directly at the Booster 37-53 MHz frequency. The DDS eliminated historic VCO problems of frequency drift and setting inaccuracies. Further the DDS allows the following:

1. The capability of switching between operational states on a machine cycle-by-cycle basis.
2. The ability to synchronize a gap in the Booster beam to the extraction kicker for a low loss, properly cogged transfer to the Main Injector.
3. A built in programmable flexibility.
4. The enhancement of long term operational reliability and maintainability.
5. Improved remote diagnostic features.

During the acceleration process, a complication arises at a point known as “transition.” To understand transition, we need to take an elementary look at the process of RF acceleration. The RF voltage across the accelerating gap is of the form:

$$V = V_0 \sin 2\pi f t$$

where f is the RF frequency and t is time. In an ideal machine any given particle that follows a circular orbit on the central axis of the accelerator and is “synchronous.” A particle is “synchronous” if it arrives at the RF accelerating gap at the correct time so that it always receives exactly the right energy gain per turn. This “time,” labeled t_s

in figure 3.1, corresponds to a phase angle on the RF sine wave known as the "synchronous phase angle" or ϕ_S.

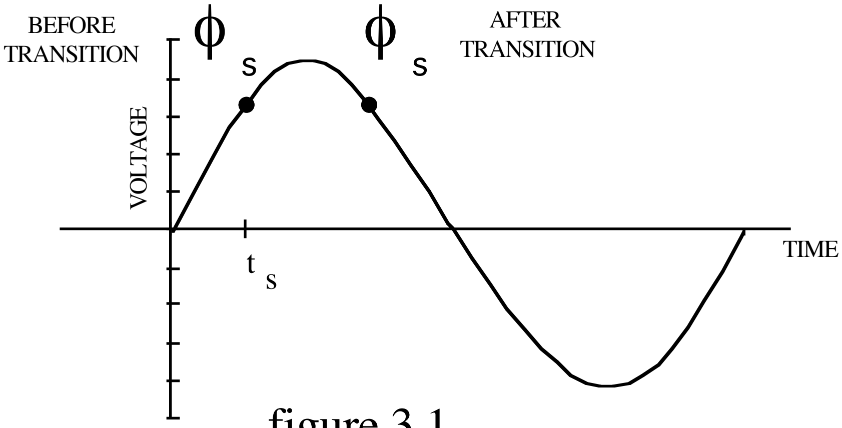


figure 3.1

In a real machine, few particles are perfectly synchronous. They do not arrive at the accelerating gap at precisely ϕ_S. A particle with higher momentum than nominal arrives at the gap too soon and sees a lower accelerating voltage. Because of this, the particle's next circuit of the machine takes longer (that is, it takes longer than a particle with a nominal momentum) and arrives at the accelerating gap later. Conversely, a particle with lower momentum arrives too late, sees a higher RF voltage, gets more energy (more than a synchronous particle) and then, on the next circuit of the machine, arrives at the accelerating gap earlier. This process is called "phase stability" and implies that all particles execute stable oscillations about the synchronous phase angle during the acceleration cycle. These are called "synchrotron oscillations."

The synchrotron frequency verses Booster cycle time is shown in figure 3.2. Please note that by definition, transition occurs when the synchrotron frequency is zero.

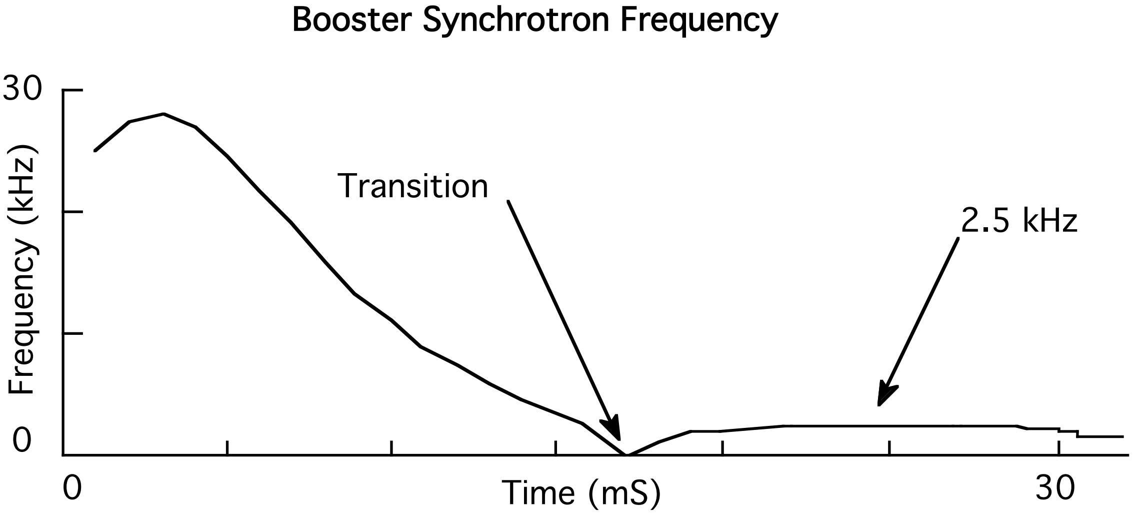


figure 3.2

The preceding discussion has been concerned with that period of the acceleration cycle where most of the energy gained by the particle goes into increasing its velocity. However, as the particle's velocity approaches that of light, an increase in energy produces little change in velocity. What does increase is the average path length the particle follows around the machine. At one point in the cycle, a change in momentum has no effect on the period of revolution; all particles take exactly the same time to circle the machine. This point is called "transition." In the Booster, transition occurs at an energy of ~4.2 GeV and occurs at about 17 msec in the Booster cycle. The transition phase jump time is a settable parameter, B:TTRXxx. (B:TTRXxx is the timer used when the Gamma T jump is not being used at transition.)

Returning to our discussion of phase stability, the mechanism described above no longer works after transition time. A particle with higher momentum than that of the synchronous particle travels a longer path, takes longer to circle the machine, arrives later at the gap and gets a larger energy boost, which increases its orbit radius. This makes it arrive even later at the gap on its next orbit, etc. Finally, this particle will be outside the stable bucket area and will be lost. Similarly, a low momentum particle travels a smaller radius orbit, arrives at the gap too soon, gets less energy gain, making it arrive even earlier the next cycle, until it too is lost. However, stable oscillations can be restored by a relatively simple maneuver. At transition time, the RF phase is shifted so that f_s is on the falling side of the RF sine wave (figure 3.1). It is left as an exercise for the reader to convince him/her-self that this scheme preserves phase stability above transition.

High Level

There are 17 RF cavities located in nine of the long straight sections of the Booster lattice. There are two stations per straight. At long straight 17 there is only one cavity; when the low-level room was expanded there was not enough room for RF station eight's modulator in the equipment gallery. The power amplifiers and the ferrite tuners (or simply tuners) are mounted on the cavities in the tunnel, while the low level RF components, tuner bias supplies, modulators for the PA's, and control circuits are in the equipment galleries upstairs. The 30 kV DC power supplies ("anode supplies") for the PAs are located in the transformer yards, one in the east gallery powering seven systems and one in the west powering the remaining ten. The High Level control in Booster is similar to that in Main Injector. The basic block diagram can been seen in figure 3.3 below. One can think of a cavity as two open transmission lines placed end to end. The cavity resonance is adjusted through the ferrite tuners while the P.A. stack distributes the modulated power.

The RF cavity contains a drift tube with accelerating gaps at both ends. The drift tube has a 21/4″ beam pipe at its center. Only this beam pipe and the accelerating gaps are under vacuum—the rest of the cavity and the tuners are at atmospheric pressure. Three bias tuners are attached to each cavity; they are coaxial transmission lines with shorted ends. The center conductor of each is connected to the center of the drift tube and the tuners are part of the resonant structure. (See figure 3.4 below)

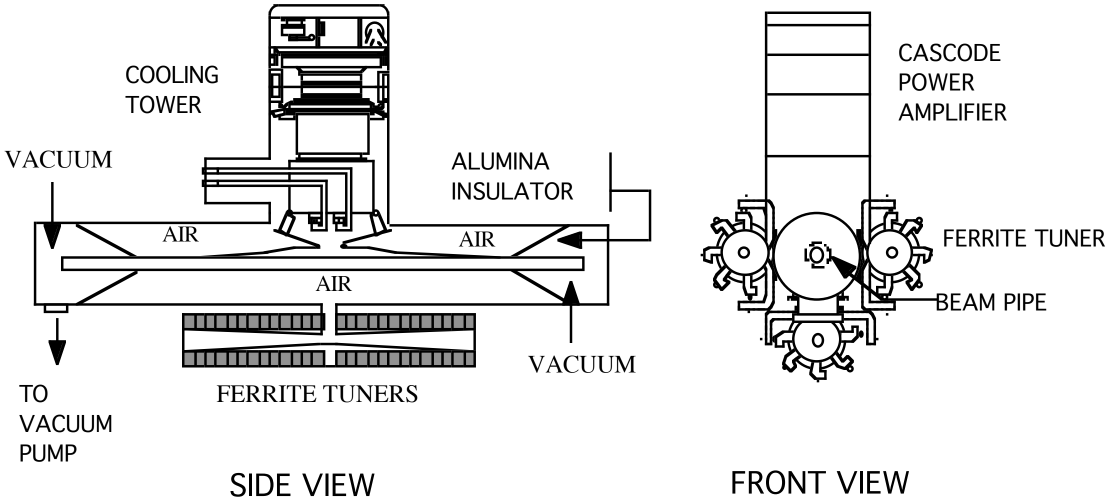


figure 3.4

The 100 kW power amplifier is mounted on top of the cavity and its anode is also part of the resonant system. Since the accelerating voltage and cavity impedance change throughout the cycle, the power output of the PA is programmed. The series tube modulator controls the anode voltage of the PA and modulating the current through the 14 cascade driver tubes varies the current gain of the cascade stage. Waveforms for the anode voltages and cascade bias are computer generated (B:APG, B:CIG).

Low Level/Feedback

The Booster low level (Radio Frequency) system supplies a reference RF signal of the proper frequency and phase to the hardware that produces the high level RF. Low level curves are loaded into waveform generators. These curves produce the low-level signals that are sent to the appropriate hardware. In addition to the low-level curves, the RF system requires the use of “real time” beam feedback systems and slow “learning” loops. At the Long 18 straight section there is a radial position detector, the radial position signal is used to represent the energy of the beam. There is also a wall current monitor used for phase detection. These signals are used by the beam feedback electronics. (See figure 3.5)

Booster LLRF

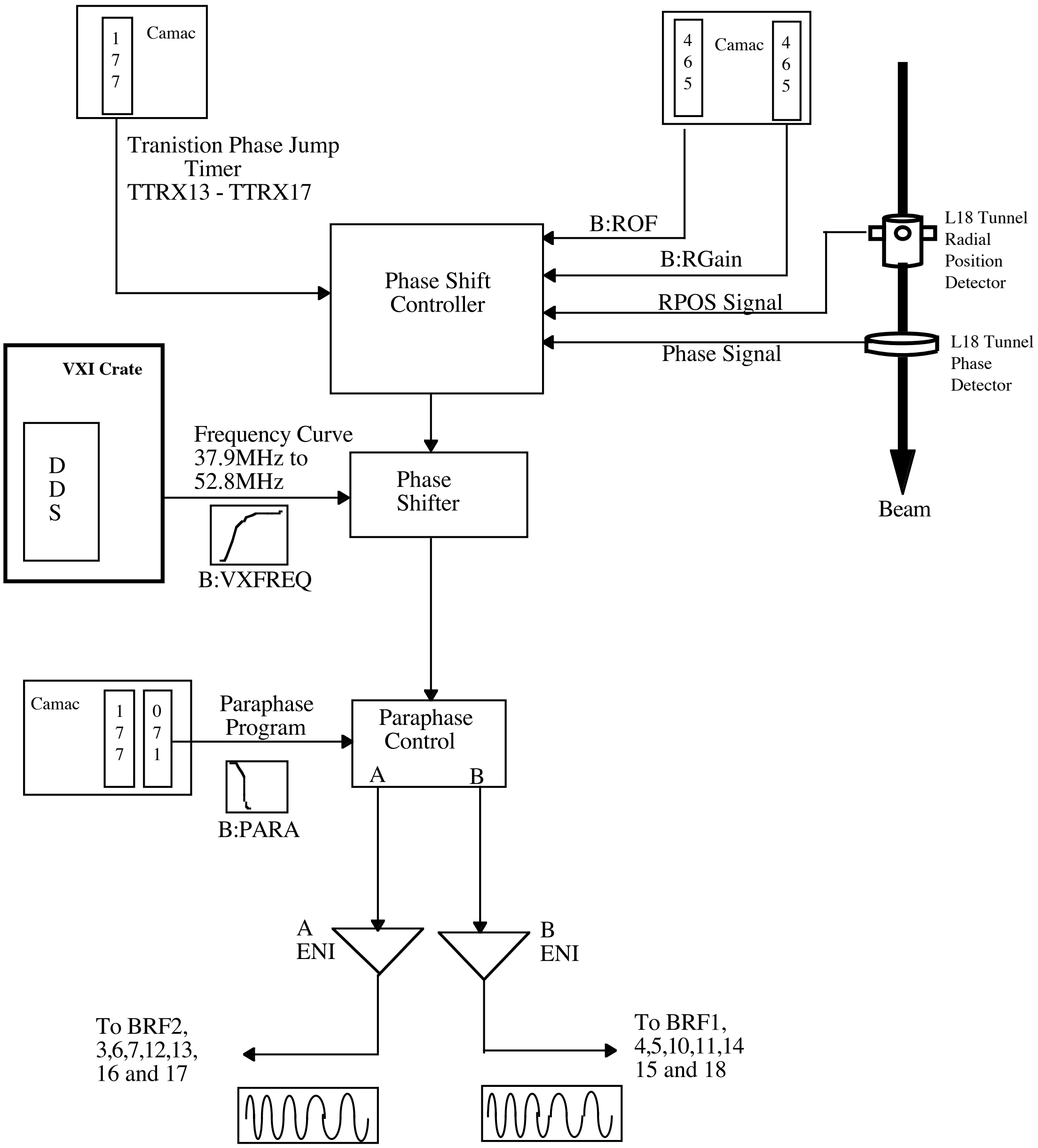


figure 3.5

During paraphasing, the groups “A” and “B” voltage vectors are brought into phase relatively slowly. A low-level paraphase curve (B:PARA) which resides on a 071 CAMAC card controls the rate at which paraphasing occurs. This particular curve is rather insensitive due to the time constraints involved in the paraphasing process. (Four of the stations have 465 CAMAC cards that can be used to make adjustments to the station's APG curve. This will allow balancing of the groups “A” and “B” voltage vectors.) Once beam has been injected, the RF frequency begins to increase. A low-level frequency waveform, B:VXFREQ, guides the change in frequency of the DDS. The DDS output increases in step with the rising magnet current (decreasing revolution time or increasing beam energy).

The RF voltage at the cavities is:

$$V_{RF} = V_o \cos(2\pi h f_{rev} t + \phi_s)$$

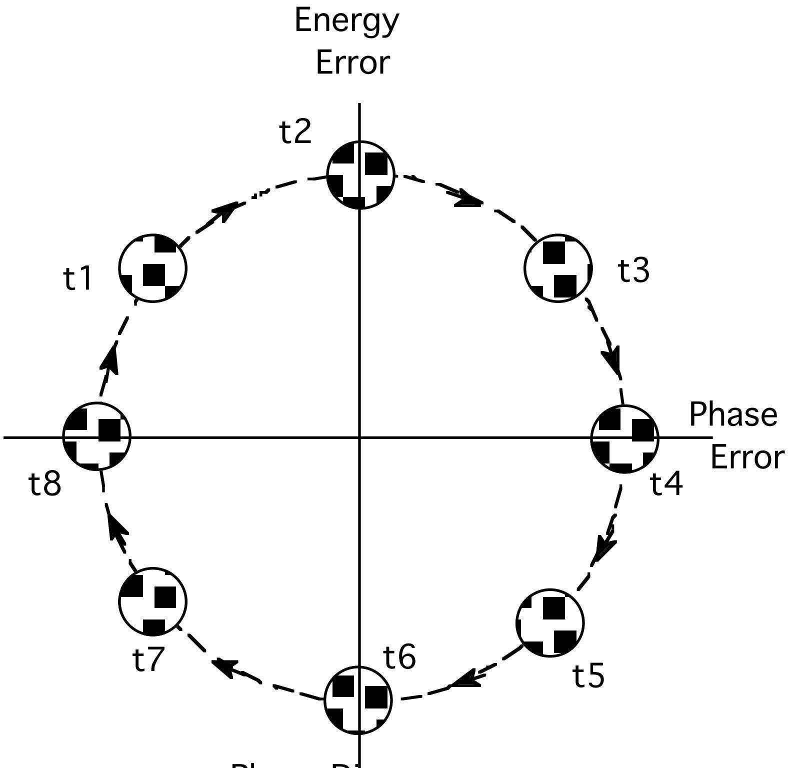
where h is the harmonic number (84 for the Booster), f_{rev} is the revolution frequency which varies from 450 to 629 kHz (the RF frequency is increased from 37.8 MHz to 52.8 MHz). The synchronous phase angle (ϕ_s), as mentioned earlier, is the desired phase between the beam and the RF voltages. Not only must the RF frequency (revolution frequency) match the beam frequency but the phase difference between the two must be controlled as well. However, since the frequency is the derivative of the phase, once the phase is right, the frequency will be correct as well.

The output of a resistive wall monitor located in the Long 18 straight section provides the phase information. There are two feedback paths in the Booster low level system: the phase lock loop (PLL) and the radial position loop.

The radial position loop uses a BPM (Beam Position Monitor), also located in the Long 18 straight, to provide information about the radial position of the beam. The radial position (RPOS) is compared to the radial offset curve (ROFF), which specifies the desired radial position through the cycle. The difference between RPOS and ROFF forms and error signal RPERR. This signal is multiplied by a gain factor specified by the RGAIN curve and then delivered to the phase shifter. The resultant phase shift causes a slight change in the net accelerating voltage per turn, and in this way maintains the desired radial position of the beam.

The PLL does beam damping as well. Assume that the beam phase and the DDS phase are locked together. If a sudden *jerk* is applied to the beam, the beam will begin to oscillate about the synchronous phase as shown in Figure 3.6. A resistive wall monitor (at long 18) measures the beam's phase error. (The damping actually requires the derivative of the phase signal generated by the resistive wall detector.) After some signal processing a correction is then applied to the RF stations. The damping is accomplished by accelerating or decelerating the beam bunches, reducing the amplitude of the synchrotron oscillation.

The phase diagram, as in figure 3.6, shows the cycling between the energy error and phase error of the beam during a synchrotron period (t1, t2, are just time 1n time 2, etc.). The radius of the circle corresponds to the synchrotron amplitude. If the beam had no energy error it would be located in the center of figure 3.6. The signal B:FPERR is a measurement of this error.



Phase Diagram
figure 3.6

The final stage of the Booster cycle involves phase locking the Booster RF to the Main Injector RF to allow a bucket to bucket transfer between the two machines. The Booster bunches maintain their bucket structure during the trip down the 8-GeV line, and if the phases are matched, the bunches will arrive into the Main Injector buckets with little beam loss. A frequency trigger initiates the phase locking process. When the RF frequency sweeps through approximately 52.805 MHz, a module containing a quartz crystal filter whose pass band is centered at their frequency generates a trigger. This frequency is below the Main Injection frequency of 52.813 MHz. During the phase lock process the frequency gradually works up to match the Main Injector frequency and phase-locks. The error signal B:PLERR is a measurement of how well the two RF systems are phase-locked. During this time the RPOS feedback is disabled. (See figure 3.7 for a general overview.)

List of curves and signals used for tuning the Booster RF system:

RF Parameter	Acnet Name	Type	CAMAC	Diagnostic Feedback
*Paraphase	B:PARA	Low Level	071	BLMON
Radial Offset	R:ROF	Low Level	465	RPERR
Radial Gain	R:RAG	Low Level	465	RPERR
*Anode	B:APG	High Level	465	BLMON
*Cascode	B:CIG	High Level	465	B:PtxxSI
*Bias	B:BIAS	High Level	071	B:PdxxE

*Not usually tuned.

The reason some of the curves reside on 465s and some on 071s is due to the fact that some of the curves need more resolution. You will notice that the anode curve does not change very rapidly, where as the frequency curve needs to be controlled more precisely through the cycle. The low level RF frequency (B:VXFREQ) is now handled by the DDS. Its diagnostic feedback is still FPERR.

Booster RF

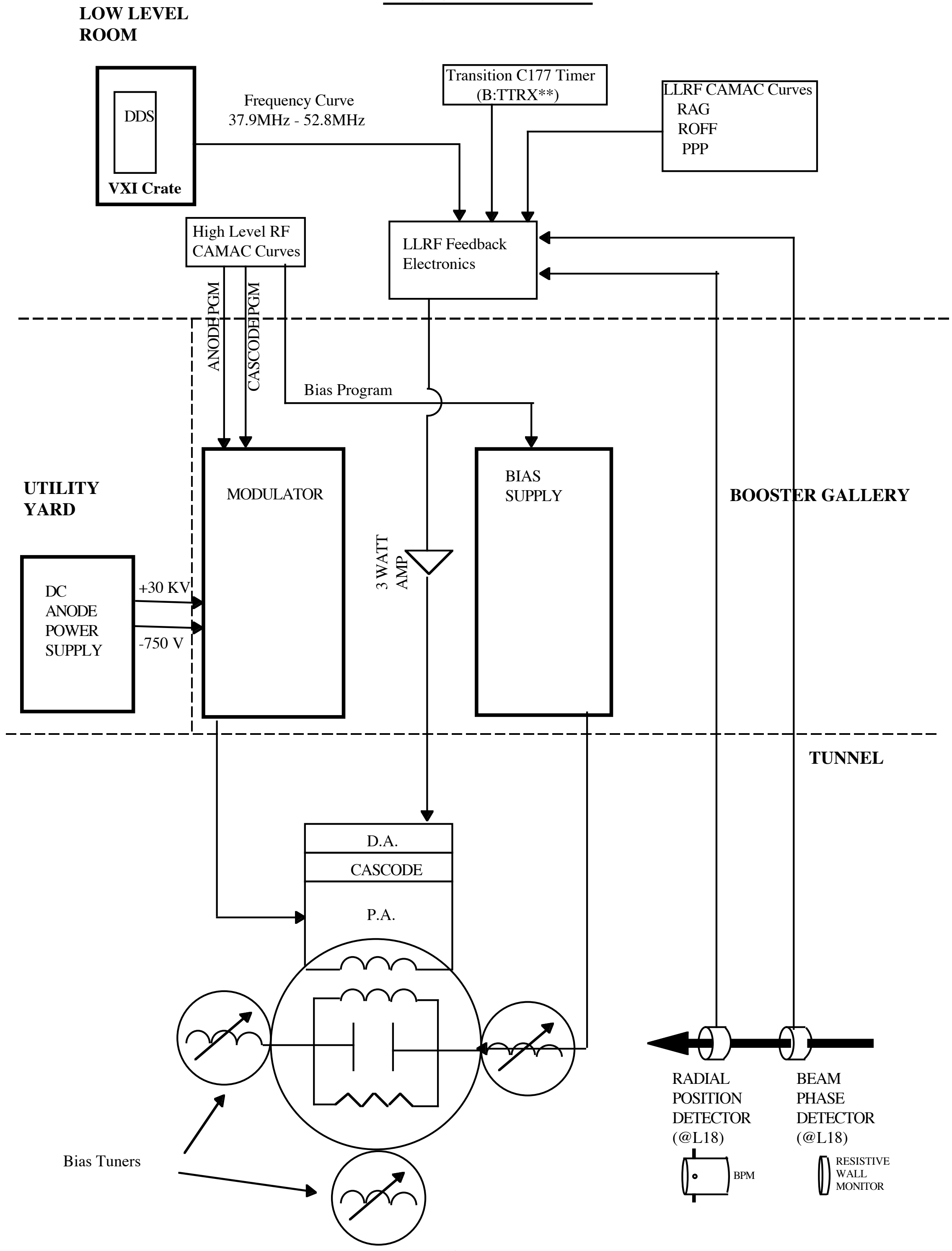


figure 3.7

Dampers

Any electric charge that passes by a conductor causes a temporary electric field. Normally, these fields dissipate very quickly. However, when the speed of the particle nears the resonant frequency of your conductor, the electric field will last for an appreciable amount of time.

Since Fermi Lab has lots of particles (beam) passing by lots of conductors (beam pipe), there are lots of resonant electric fields induced on the beam pipes. The resonant electric field caused by one part of beam will cause errors in the following beam. We call these resonant electric fields <u>wake fields</u>, and we try to "dampen" them out (cancel out the errors caused by the fields). Wake fields occur due to the impedance of our beam pipes. All electric devices have natural resonant frequencies. These are frequencies that give a theoretically infinite output for any input. The impedance of the system determines which frequencies are resonant. Thinking of our pipe as a circuit, if I (beam) goes up and R (the beam pipe) stays the same, V (our wake field) also increases:

$$V = I * R$$

wake field = beam * impedance

So, the more beam you have, the more important dampers become. In fact, running any beam over 4E12 in Booster requires damper operation.

The way that we dampen the beam is with a pick-up/delay/kicker system (see Fig 3.8). The *pick-up* finds the error of the beam. The deflector plate (called a *kicker*) gives energy to the beam in order to offset the error. These kickers should not be confused with the Booster extraction kickers. The *delay* makes sure that the kicker effects the same place in the beam that the error was found. The pickups in the Booster live at long 17; this is why tuning here should proceed cautiously when the dampers are being used. The coupled longitudinal Booster dampers use the RF cavities as their kickers and the coupled transverse Booster dampers have their own kickers.

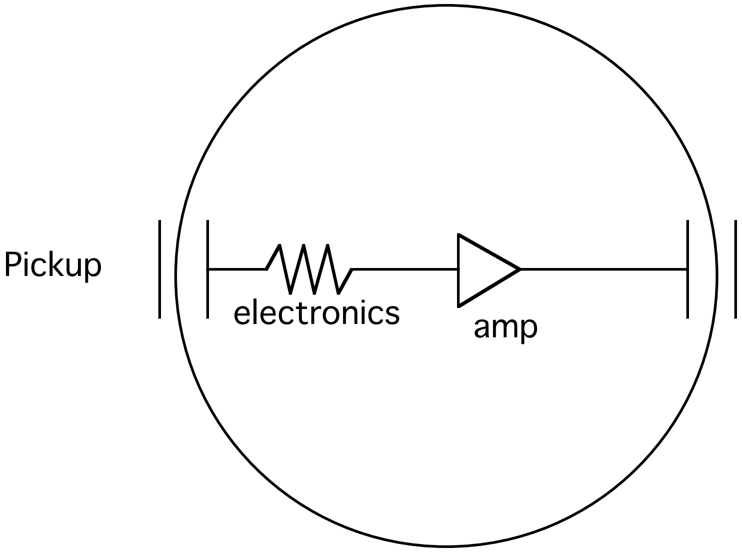


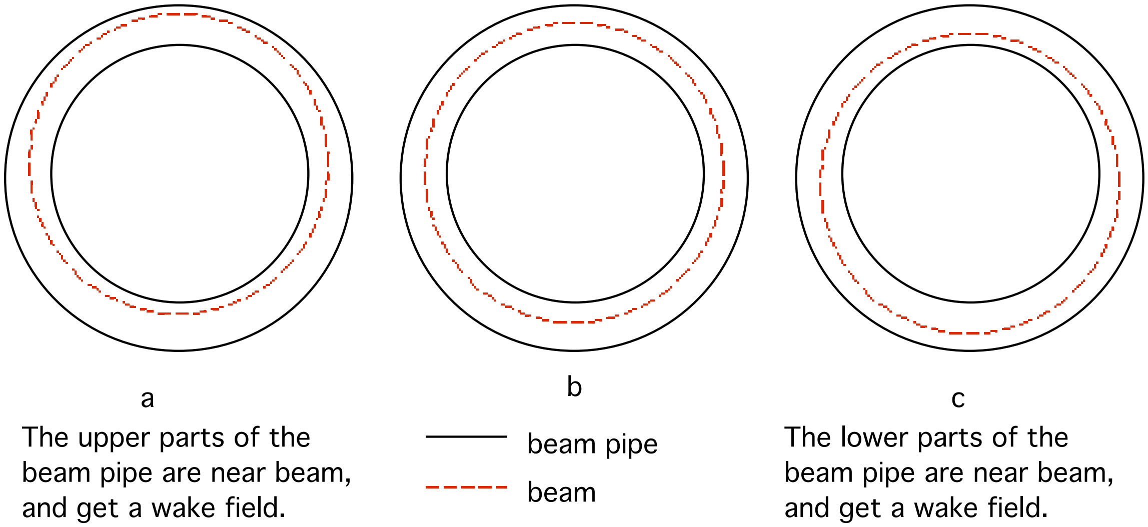
FIGURE 3.8

There are many wake fields at different frequencies induced on beam pipes. However, the only wake fields that we worry about are those that are resonant (the others fade away so quickly that they don't have much effect on beam). The particular frequencies that we dampen are called *modes*. There's no great mystery as to why some frequencies are resonant and some aren't. It's just a function of the physical dimensions of the beam pipe and the speed of beam particles.

There are many ways that beam can oscillate and cause a resonant field. The two types of oscillations we dampen are **bunch to bunch** and **coupled bunch** oscillations. These two are the difference of one bunch affecting the following bunch, and the connected beam affecting itself.

Bunch to Bunch: One bunch passes through the beam pipe and produces the wake field, thereby effecting the next bunch. This type of damper is not presently used in Booster.

Coupled Bunch: If you looked at the entire beam in any one instant, you would see the group of bunches at different positions in the beam pipe (see Fig 3.9). The beam toggles through these positions as it progresses through the machine (a to b to c to b to a to b etc.) This oscillation causes a wake field on the beam pipe.



a
The upper parts of the beam pipe are near beam, and get a wake field.

b

c
The lower parts of the beam pipe are near beam, and get a wake field.

FIGURE 3.9

Figure 3.9 is an example of a mode 0 coupled bunch oscillation.

Resonant frequencies only come from a force driving them. Just think of a swing. If you push a person on a swing at the right time (at either end of their arc) they will go higher and higher on their swing. Even if you push them every second time or every third time they come to the end of their arc, they will still go higher. However, if you start pushing them at the wrong times (ex: at the bottom of their swing, or pulling them when you should be pushing) they won't go much higher. In fact, you can say that the resonant frequency of any system can only be a multiple of its driving force. The actual beam (RF frequency is the same frequency as when the beam arrives) and the synchrotron frequency (how often the beam rotates inside the bucket) drive the Booster's wake field resonant frequencies. Putting this in a mathematical form:

Mode X's frequency = RF frequency + (X * synchrotron frequency)

In the Booster, our coupled bunch dampers work on modes 1, 48, 49, and 50. These modes were picked because damping them gives us the greatest increase in beam stability and intensity.

Both of these errors are electronically handled in different ways. Suffice it to say that coupled bunch has a high frequency effect on the beam and gets damped in all machines, whereas bunch to bunch is a lower frequency effect.

Finally, each damper has two more defining characteristics depending upon which oscillations it's supposed to dampen out. The first of these characteristics is the direction of beam motion that it is damping.

Transverse Damper: Damps beam oscillation that is perpendicular to the direction of beam. This is the common type of wave that you notice most in nature. Like a water wave, the wave moves towards the shore, but the water goes up and down.

Longitudinal Damper: Damps beam oscillation that is parallel to the direction of beam. You can think of this wave by imagining a slinky. If you push one side of a slinky towards the other, the slinky will get bunched up where you're pushing. This "bunching up" will travel down the length of the slinky.

The other characteristic that we use to identify a certain damper is the range of frequency operation.

Narrow Band Damper: A damper that has a narrow frequency range, but can put more power into the frequencies that it will dampen.

Broad Band Damper: A damper that has an unlimited frequency range, but the power is diluted since it is being spread over a wider frequency range.

CONTROLS

The hardware for each damper is different, but all of the hardware lives in the Booster LLRF room. Each mode of the coupled bunch longitudinal dampers uses two NIM double wide cards to get the basic frequency, two RF amplifier cards to generate a clock signal, and one as an amplifier, a phase shift card and CAMAC 465's to add another phase shift due to Booster's frequency shift. The coupled bunch transverse dampers use a VXI.

The dampers have a number of knobs to tune on. The initial tune-up of a damper includes tuning 1) delay timing, 2) the way the beam is broken into constituent parts to remove different frequency error (called superheterodyne sin/cos split) and 3) the CAMAC 465 cards to change the phase difference between pickup and kicker. During normal operation, we should only have to tune the 465 cards.

MORE THEORY

It is totally unnecessary to read or understand this section for good operation of the machine. However, this section allows you to understand how and why to tune the dampers, and what kind of errors the dampers could cause.

Betatron Oscillations:

One problem we have with a damper pick-up is that it always expects the beam to be in the center of the beam pipe. If the beam deviates at all (as in the expected and good betatron oscillations), the pick-up will think the beam is in error, and tell the kicker to correct for this error (gasp!).

Thus, we are faced with the problem of how to ferret out what is an error and what is a betatron oscillation. The idea behind the fix is that if the beam changes drastically between successive passes of the machine, then we have an error. Otherwise, the beam is remaining at approximately the same position pass after pass, and the position should not be corrected. In other words, this adjustment takes care of high frequency errors (errors that change once every pass) in the beam's position. Do not confuse this with coupled bunch oscillations. Coupled bunch oscillations are the relative position of bunches changing many times per pass. However, this high frequency error is the position of bunches with respect to the center of the beam pipe. To check for a drastic beam change, the electronics compares the current position of the beam to the previous position of the beam. The electronics then subtracts these two readings. This subtracted signal is fed into the kicker. Therefore, if there is a small change between the beam's current position and the previous position, there is almost no kicker signal. But, if there is a big difference between the current and previous position, then the kicker receives a large signal.

The positions are read into a circular buffer. The data is placed in successive positions of memory, and stored there until there isn't any more room for new positions. At that point, the next value of position overwrites the oldest position of the beam stored in memory. The counters tell you where in memory you are currently writing and reading. Two clocks function as the delay, and release the error signal to the kickers. Each bucket is stored separately in memory, and so the number of bunches/beam pulse is stored as well.

Error Signals:

The electronic handling of the error signal gives greater insight into what to tune and how to tune.

Looking back at figure 3.9, the mode 0 coupled bunch oscillations are WITH RESPECT TO the RF phase. If we were to represent each bunch of 3.9.1 on a phase error vs. time plot, we would see:

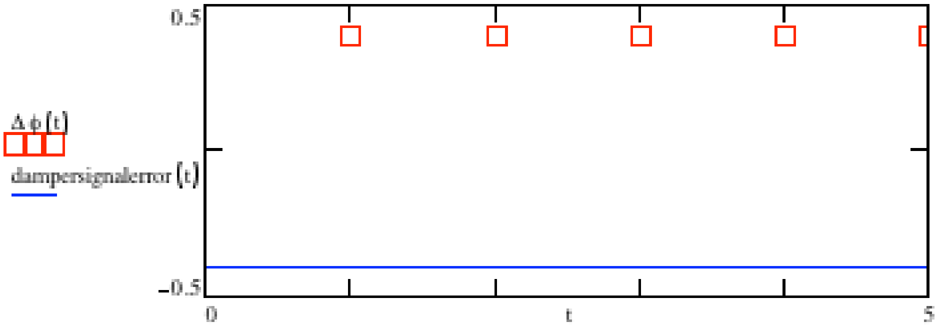


Figure 3.9.1

Each bunch has a phase that is a bit larger than the proper RF frequency. To correct that, we reduce their phase the same amount through the normal phase corrections in booster. We don’t need a damper, we just give a DC offset (reduction) to the RF voltage. So, the amount of RF push goes down, but this means that 3.9.1) is a little lower and 3.9.3) is a little higher.

A mode 1 coupled bunch oscillation plot looks this:

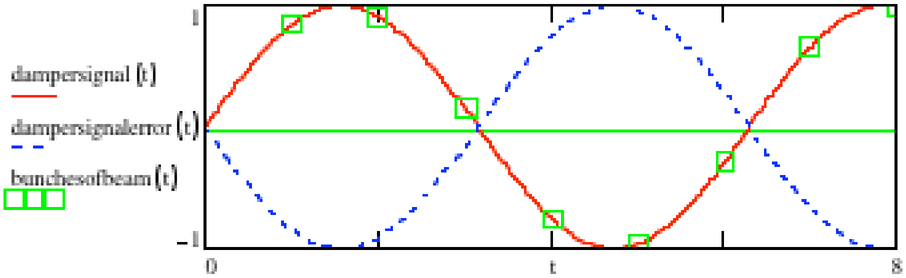


Figure 3.9.2

Here, different bunches of the beam have different phase errors with respect to the RF frequency. To dampen this mode 1 error, our damping signal must completely match the error signal, but be 180 degrees out of phase with the error. In fact, when you tune the dampers, you are changing the phase offset of the damper signal. We want 180 degrees out of phase exactly, and this will dampen most effectively. If our signal is a little off:

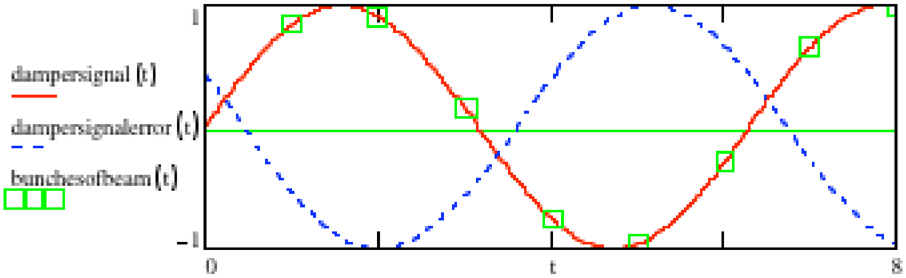
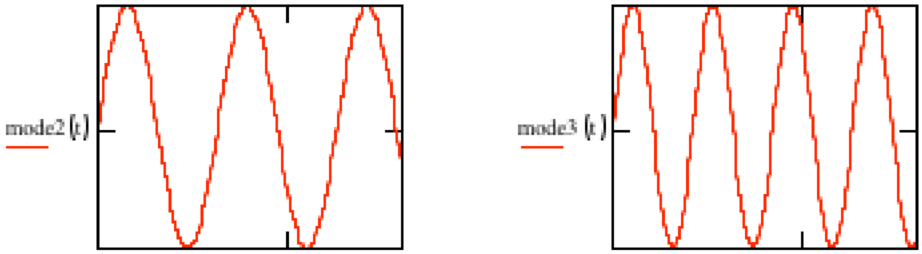


Figure 3.9.3

we need to reduce the phase of the damper signal to get it exactly 180 degrees out of phase with the damper signal.

The higher modes are very similar to mode 1, but their frequencies become higher and higher



MODE 2 MODE 3

Figure 3.9.4

Why is the RF used as our kickers?

Some people notice that only the Booster uses the RF cavities as kickers. Why is that? To explain, we must understand what Quality Factor is. Alternating current (AC) electronic circuits store (inductance, L and capacitance, C) and use (resistance, R) energy. The relationship of the two amounts is combined into quality factor:

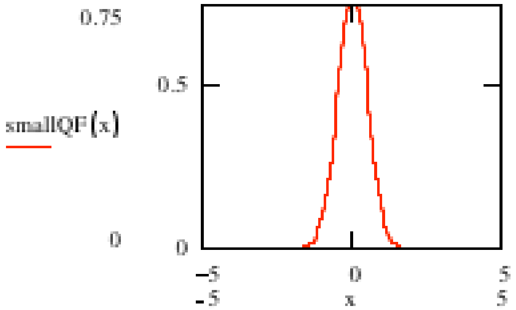
$$\text{Quality Factor, Q} = (2 * \text{pi}) * \frac{\text{maximum Energy stored}}{\text{total Energy lost per period}}$$

for most circuits, we use the value:

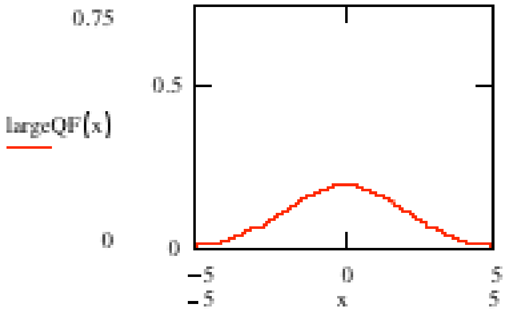
Q = R * sqrt(C divided by L) = R divided by X = R divided by X
(don't worry if you don't know what X or X are).

Q is just a number that describes how fast our system uses up its energy. Even a bouncing basketball has a Q factor. The more bouncy the ball, the larger the quality factor. In other words, it loses just a little E for every bounce, or that it is very efficient if you keep dribbling the ball at the proper frequency. If you try to dribble at the wrong frequency (slapping the ball when it's on the floor), it's not going to work very well.

Amplifiers do this same thing. They are made to amplify a certain frequency. Q factor tells us how much amplification we get at a different frequency:



Circuit outputs only very near desired frequency = good

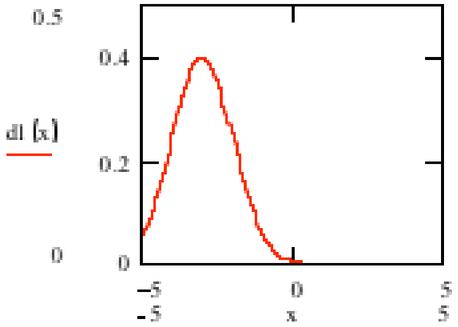


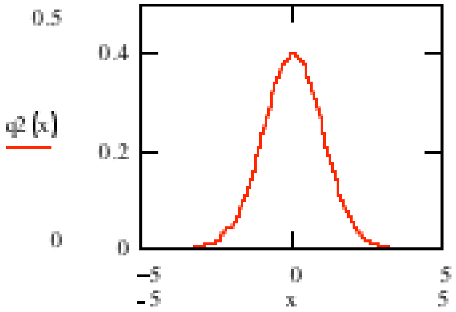
Circuit outputs over large frequency range = bad

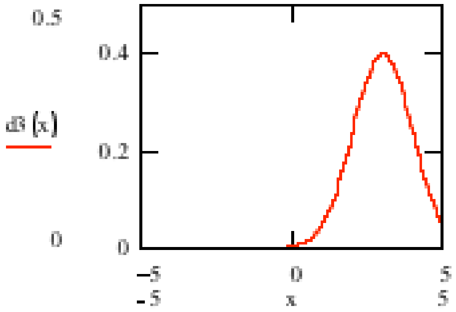
Although we want a large quality factor, the Booster PA's have a reasonably small one. This is good for the damper folk. Usually for a damper system, you've got to build an entirely new amplifier that amplifies at the frequency that you want to dampen. The Booster gang had some trouble getting that done, and they looked at the Booster RF for inspiration. Since controlled bunch oscillation occurs near the RF frequency, the Booster PA's are capable of amplifying the desired mode. Although the PA's response is obviously diminished the farther you get from the RF frequency, this is still enough to dampen our desired modes.

Dipole vs. Quadrupole Motion

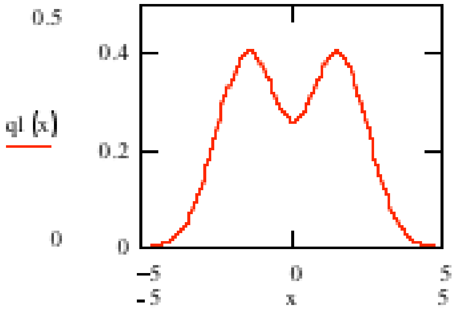
So far, we have talked exclusively about dipole motion. The change of energy can be seen in the previous section. The energy of the beam goes back and forth around where it should be:

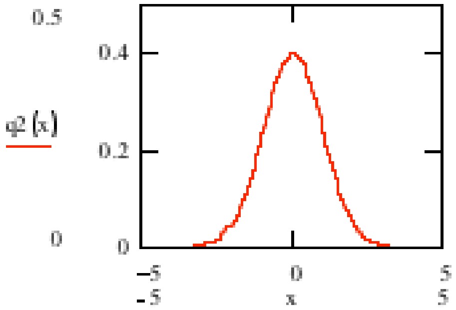


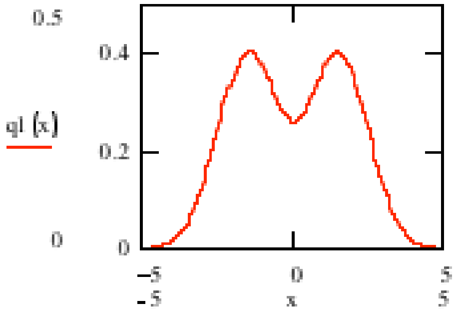




However, there is also a quadrupole error that is found inside of the bunch. In this case, the bunch has the proper average energy, but the distribution of the bunch is wrong:







So, dipole motion has the entire bunch position oscillating around the desired energy, where the quadrupole motion has the average position of the beam at nominal, but the inner particles are off positionally.

Gamma-T

The machine lattice defines the transition energy of an accelerator. While the beam is near the transition energy, instabilities can cause emittance growth in the beam. A system was implemented to reduce the time that beam spends near the transition energy by momentarily changing the lattice. Quadrupoles, located in the even-numbered short straight sections of Booster, are used for the transition-jump system. Half of the twelve quadrupoles are focusing and the other half are defocusing. Reducing the amount of time the beam spends near transition, suppresses certain effects which dilute the longitudinal phase space of the beam. This system is not useful against so-called microwave or negative-mass instabilities. But this system is useful in reducing bunch-length oscillations after transition.

The system is designed to cause a rapid reduction in G_t (the lattice parameter, not the beam energy) so that the rate of passage through transition is increased by a factor of 25. The transition phase-jump timing needs to be moved nearly 1 millisecond sooner when the Gamma-T quads are pulsed due to the reduced transition energy. The quadrupoles are arranged in such a way that there is little or no net tune shift ring-wide.

Correction Elements

No matter how well an accelerator is designed, once built it never performs exactly the way it was supposed to. There are manufacturing defects and variations in the magnets and power supplies that cause the beam to behave differently than predicted. There will also be manufacturing defects in the main magnets, such as variations in the dimensions of the laminations. Since the magnet laminations are stamped from sheet steel, the dies wear and the size of the stampings can change. When the laminations are stacked, they do not always line up precisely, resulting in variations in effective length or magnet tilts and twists. Magnets can also be surveyed into position incorrectly.

Because of the inconsistencies in field strength and quality, additional magnets or "correction elements" were inserted in the Booster lattice at the long and short straight sections. These correction magnets can correct for DC errors in the gradient magnets such as remnant field effects and stray fields, which remain constant during the cycle. The correction elements can also be ramped to correct for AC errors in the field of the gradient magnets. Otherwise, these AC errors increase as the field increases.

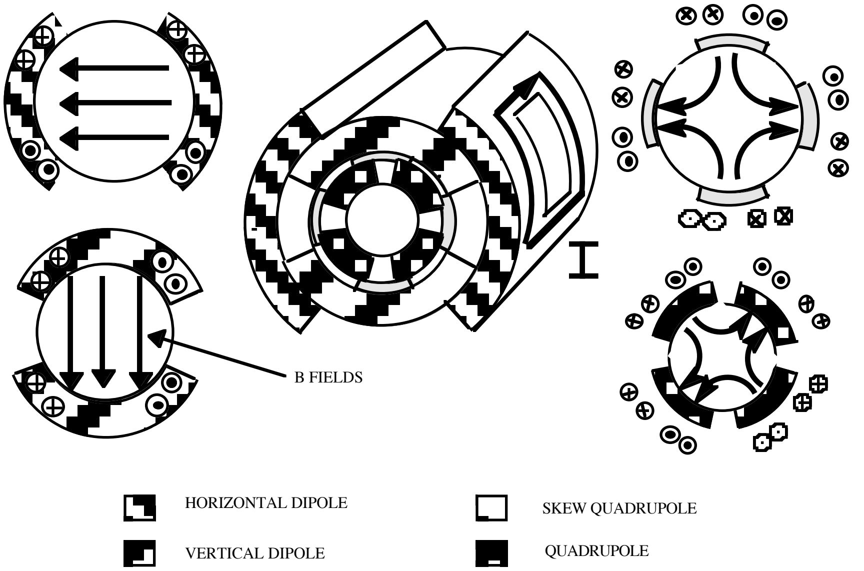


figure 4.1

There are five types of correction elements used in Booster: dipoles, quadrupoles, skew quadrupoles, sextupoles, and octupoles. At each long and short straight section there is a "correction element package" consisting of a vertical dipole, a horizontal dipole, a skew quadrupole and a quadrupole all nested within each other (figure 4.1).

There are also sextupoles, skew sextupoles, and octupoles, used to correct higher order field errors. There are eight correction element power supplies located at four points in the equipment galleries used for all elements except the octupoles and sextupoles, which have dedicated supplies. The eight bulk supplies provide power to the correction elements through amplifier modules allowing independent control. Each module powers the four correction elements making up the package at each long or straight section (figure 4.2).

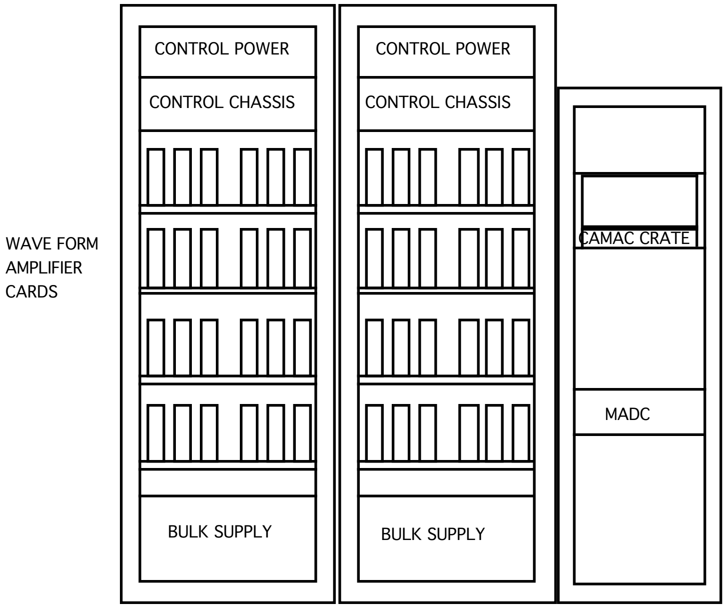


Figure 4.2

Dipole correction magnets make local position changes in the beam and keep the beam centered in the magnet's aperture. Field errors or misaligned magnets can cause a miscentered beam. Occasionally, there's a foreign object in the beam pipe that may require a position change to prevent losses. The dipoles were designed to introduce a separation of 1.4 cm at 10 meters at injection energy (a period is about 20 meters long). These dipole correction elements are run DC. This means that the dipole's bending strength diminishes in direct proportion to the beam's momentum. At 8-GeV, Booster dipoles are bending the beam about 14 times less than at injection, even though the kinetic energy of the beam increases by a factor of 20 between 400 MeV and 8 GeV. The momentum increases from .956 GeV/c to 8.93 GeV/c. Fortunately, field quality in the main gradient magnets generally improves as the magnet current increases. Also, the cross-sectional area of the beam is reduced by a factor of one over the square root of the momentum. In the case of Booster, the cross-sectional area of the beam is reduced by more than a factor of 3 by the time extraction occurs.

Horizontal and vertical correction dipoles are normally used to produce a localized orbit displacement called a “bump” If an individual dipole were to be changed, this would create a bend angle that would result in a position displacement throughout the ring. Bumps are combinations of several magnets that are changed together in a predetermined ratio known as a “mult.” By changing the magnet currents in the proper ratio, the bump will cause a local position change in the beam without changing the orbit of the entire ring. There can be bumps made up of horizontal short (HS, vertical short (VS), horizontal long (HL or vertical long (VL straight section dipoles. Although there are both vertical and horizontal correction dipoles at each straight section, the bumps normally used are a series of consecutive vertical long or horizontal short, straight section dipoles.

The most frequently used bumps in Booster are made up a series of three dipoles and are known as “three bumps” although four bumps are also used. Bumps made up of more elements are also possible. Due to the fact that the beam cross section is larger vertically in the long straight sections (a consequence of a property of the lattice known as the Beta function), vertical long bumps are normally tuned and vertical short bumps are typically not used. Likewise, beam has a larger horizontal cross section in the short straight sections, so horizontal short bumps are used the majority of the time, with the horizontal long bumps left alone. Also the field quality of correction elements degrades towards the center of the beam pipe, so a larger beam will experience better field quality on the average.

As beam passes through the series of three dipoles making up the three bump, each magnet imparts a bending force on the particles. By using the correct ratio of bend angles, the beam can exit the last correction dipole having the same trajectory that it would have had without the bump. If the ratios are not correct, there will be oscillations created around the entire ring. This is known as a “non-local” bump. A non-local bump can cause losses at other points in the ring. It is important to remember that each of these three bumps span 60 meters. Although the greatest displacement will take place at the middle dipole in the series of three, there will be some displacement of the entire distance. Since the largest position change does take place at the middle dipole, a three bump made up of dipoles VL7, VL8, and VL9 is called a VL8 three bump. In addition to the DC bumps, there are presently two sets of ramped dipoles. VL3P and VL13P are group names which allow a ramp the normally DC three bumps, VL03:3 and VL13:3. The ramps allow for orbit control through the entire Booster cycle. These locations were chosen because of their aperture restrictions. The need may arise with higher intensities for more ramped dipoles.

Calculating the ratios of magnet currents used in a bump can be a bit more complicated then it might first appear. The beam undergoes stable betatron oscillations due to the focusing of the gradient magnets and this must be considered when making the bump calculation. The term “phase advance” is used to describe how far through a betatron oscillation the beam has traveled. Fortunately, the ratios have already been calculated and are handled automatically through the computer system.

The quadrupole correction elements are used to shift the tune of the machine through the cycle. The gradient magnets provide most of the focusing, and bring the tune close to the nominal values of n(x)=6.7 and n(y)=6.8. The correction quadrupoles are capable of producing a tune shift of about 0.6. Unlike the dipole correction elements, the quadrupoles are ramped—that is, the current is increased as the beam momentum increases, allowing the same level of tune control through the entire cycle. The long straight quads have more effect on the vertical tune than the horizontal by a factor of roughly 2:1, and the opposite is true for the short straight quads. Long straight quads are used for vertical tune control and the short straight quads are used for horizontal tune control. In addition to ramping the correction quadrupoles, a DC offset can be added to the output (053 card). By tuning the DC level of a series of quadrupole magnets around the ring in proper ratios, one can reduce losses due to certain resonances (half integer and integer). The output of the power supply is the sum of the DC level and the ramp wave form. (See figure 4.3)

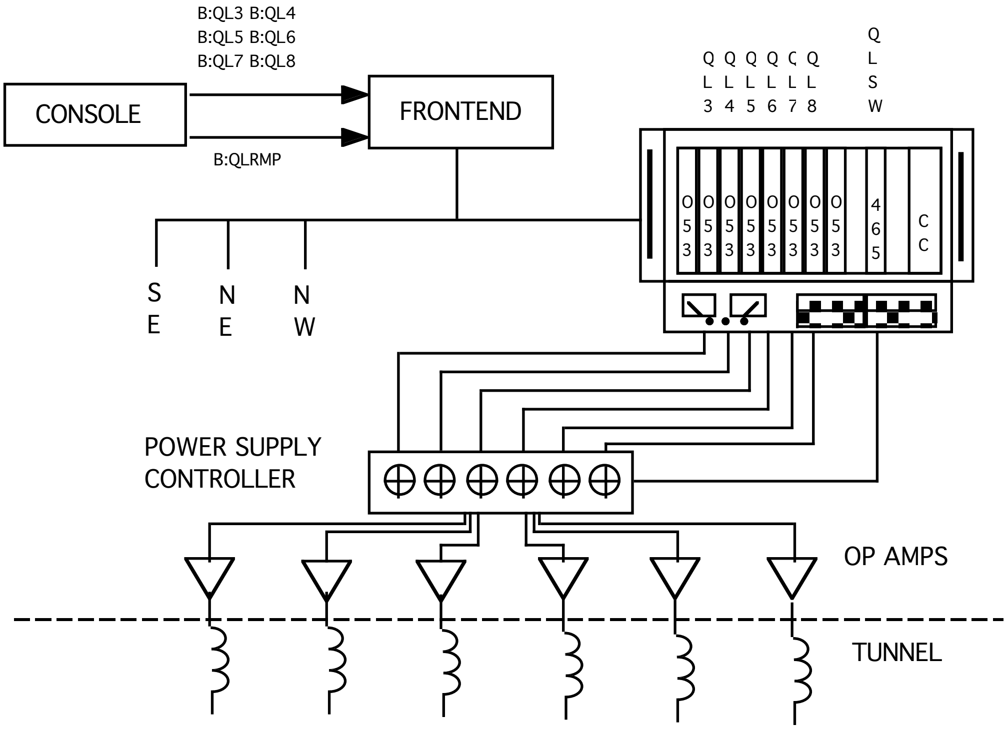


figure 4.3

Skew quadrupoles are used to prevent coupled resonances. Skew quadrupoles have their pole faces centered on the horizontal and vertical axes of the vacuum chamber, while a normal quadrupole has its faces rotated 45 degrees off axes. Coupled resonances occur when An(x)+Bn(y)=an integer (A and B are any integer, n(x) and n(y) are the horizontal and vertical tunes), or An(x)-Bn(y)=an integer. The first is known as a “sum resonance” and the second is known as a “difference resonance.” Coupling between the planes can occur when the main magnets or correction quadrupoles are rotated from their correct alignment. This can result from surveying errors, or settling of the tunnel floor. The main magnets can also have individual laminations that are not properly aligned within the magnet. Like the quadrupole correction elements, the power supply output is the sum of a DC offset and a ramp wave form.

Sextupoles are used to control chromaticity. Chromaticity is caused by the fact that particles of different momentum will not see the same amount of focusing by the gradient magnets and correction quadrupoles. A higher momentum particle going through a quadrupole field will be focused less than its lower momentum counterpart and will therefore undergo fewer betatron oscillations. Chromaticity is a consequence of having focusing magnets in an accelerator, and the term “natural chromaticity” describes the uncorrected chromaticity of an accelerator resulting from the lattice. The reason that chromaticity needs to be corrected is because of the tune spread that results. The beam has a distribution of momentum, and chromaticity causes a distribution of tunes, which is known as the “tune spread.” A large tune spread would cause some of the particles to cross resonances, resulting in beam loss. In the Booster, special end laminations were used in the gradient magnets to offset much of the natural chromaticity of the Booster. Sextupole magnets provide the remaining chromaticity control.

The Booster did not originally have sextupole correction magnets, but it became quickly apparent that they were needed. Main Ring style iron core magnets were used in studies and proved useful to improve efficiency. Air core magnets were then fabricated and put into use. Sextupoles are not part of the correction element packages, but are separate elements. “Sextupole shorts” are located at half, or all the odd numbered short straight sections (they were originally at every short straight but half were removed when the Gamma-T quadrupoles were installed in their place) and are used to control horizontal chromaticity. “Sextupole longs” are grouped in three of the long straight sections (four elements each) at long 4, 10, 18, and are used to control vertical chromaticity. Sextupole supplies are ramped, allowing chromaticity control through the entire cycle.

Harmonic corrections to the third order resonance at 6.667 is handled with sextupoles, but in a different fashion than that used for the quadrupoles and skew quadrupoles. Instead of using DC offsets on the individual sextupoles, there are separate sextupole circuits for the corrections. There are pairs of normal and skew sextupole magnets located in the period 4, 5, 7 and 6 long straight sections.

Two power supplies are connected in series to pairs of normal sextupoles and two power supplies are connected in series to pairs of skew sextupoles (in both cases long 4 and 7 for one, and 5 and 6 for the other).

There are also four octupole magnets located in the period 8 and 20 long straight sections. Octupole magnets are used to compensate for variation in tune resulting from betatron amplitude (larger amplitude particles being focused differently than smaller amplitude particles). This is not nearly as serious a problem as chromaticity, and changing the magnet current or turning it off entirely does not have a profound effect on efficiency. These magnets are run DC from a single power supply. Therefore, the octupoles will have their greatest effect at injection.

Booster LCW

Cooling water dissipates heat generated by the resistance of the magnet assemblies and power supplies. It is convenient and economical to have the cooling water share the same path as the magnet current, therefore the bus has been hollowed out to provide this path. But there is a potential problem with using a conventional water supply and circulating it through the magnet bus. Electrolysis would occur where large voltage potentials exist and would damage the metals used in the bus-work and magnet windings. Low Conductivity Water (LCW prevents this from happening, as well as for providing a path to ground.

LCW also cools the other numerous heat loads associated with the Booster both in the galleries and in the tunnel. The Booster 95 degree LCW system provides the majority of the cooling. The 55-degree LCW system has a branch in the Booster tunnel, but it's valved off and not used for anything. There is also a glycol cooling system used for the anode supplies that heat exchanges with the 95-degree system.

The Central Utility Building (CUB is the source of the Booster 95° LCW, pumps, and heat exchangers as well as a water supply to make up for losses. Make-up LCW is kept in a 3,000 gallon tank to provide water for losses due to leakage. There is also an expansion tank that has a small glass tube on the side to view the water level. An electronic eye monitors the level of the meniscus in the tube. If the level goes below a certain point (indicating that more water is needed in the system), then a signal is sent to the "three-way valve." The valve changes its position and allows LCW to flow from the 3,000 gallon tank into the system. This valve can be manually actuated if necessary.

At CUB, the LCW originates as conventional water, which enters the south side of the building and is directed through five De-Ionization (DI) bottles. DI bottles remove free ions by "polishing" the water. After polishing, the LCW is directed into the 3,000 gallon storage tank located on the southwest end of CUB. Water from the tank is kept polished by circulating it through four DI bottles located next to the tank. Either of two pumps (only one pump is used at any time) located next to the tank, circulate the LCW through the bottles.

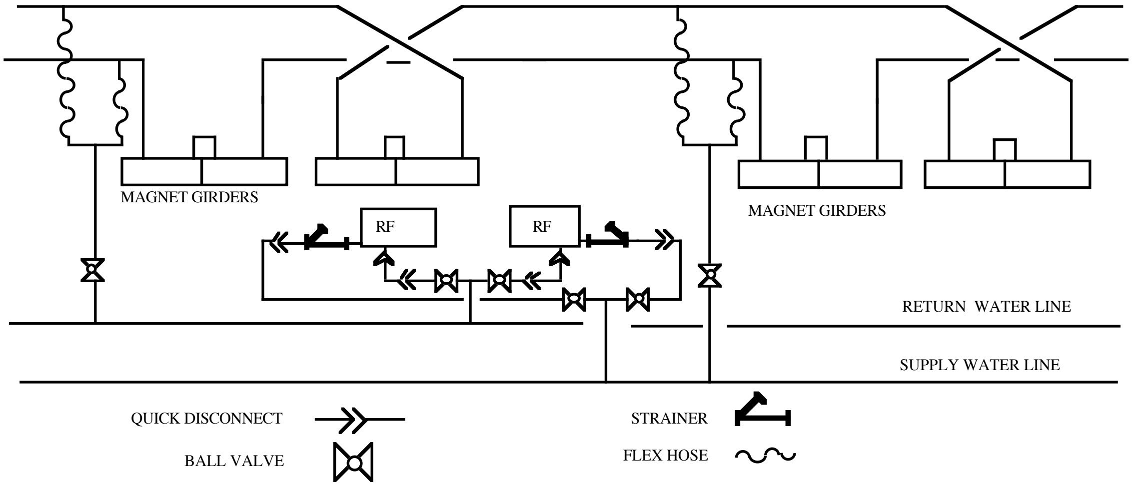


figure 5.1

Water is pumped from the 3,000 gallon tank (by the same pumps mentioned above) to the three-way valve and flowmeter located on the northern side of CUB. If there is little demand for make-up water, after a period of time the three-way valve is switched so that the water is allowed to flow back to the DI bottles and the 3,000 gallon tank. This keeps water from going "sour" by sitting in the valve line too long. The flowmeter located near the three-way valve keeps track of how much make-up LCW is being used. When make-up LCW is required by the system, it flows through the valve and flowmeter to another five DI bottles, then from there to the 95° supply header. There are two other sets of DI bottles located near the three-way valve: One is used by the 55° LCW system, and the other is used by the Pbar 95° LCW system.

There are three ACNET parameters relating to make-up flow that are returned via the control system. B:95WMUF (for 95° LCW Makeup Flow) indicates the instantaneous rate of the make-up flow. An alarm is normally posted when the flow occurs to alert the Operators of the situation. Occasional make-up flow is normal, but repeated episodes of make-up usually indicate a leak in the system. B:95LEAK (for 95° LCW Makeup Flow Averaged) shows the amount of LCW lost from the system. The parameter B:95WTOT (for 95° LCW TOTalizer) is a running summation of the amount of LCW that was taken from the reserve tank. This parameter can be used over time to indicate the loss rate in the system. A control card in a crate in the CUB control room receives pulses from the flow meter downstream of the three-way valve. The card translates the pulses into flow and routes the signal back through the control system.

Three pumps, located upstairs at CUB, maintain the LCW pressure for the Booster 95° system; only two are used a given time. There is a large orange valve attached to the ceiling above the pumps that regulates pressure. The valve is adjustable by a pneumatic controller on the wall by the pumps, and is normally set to 165 lbs.

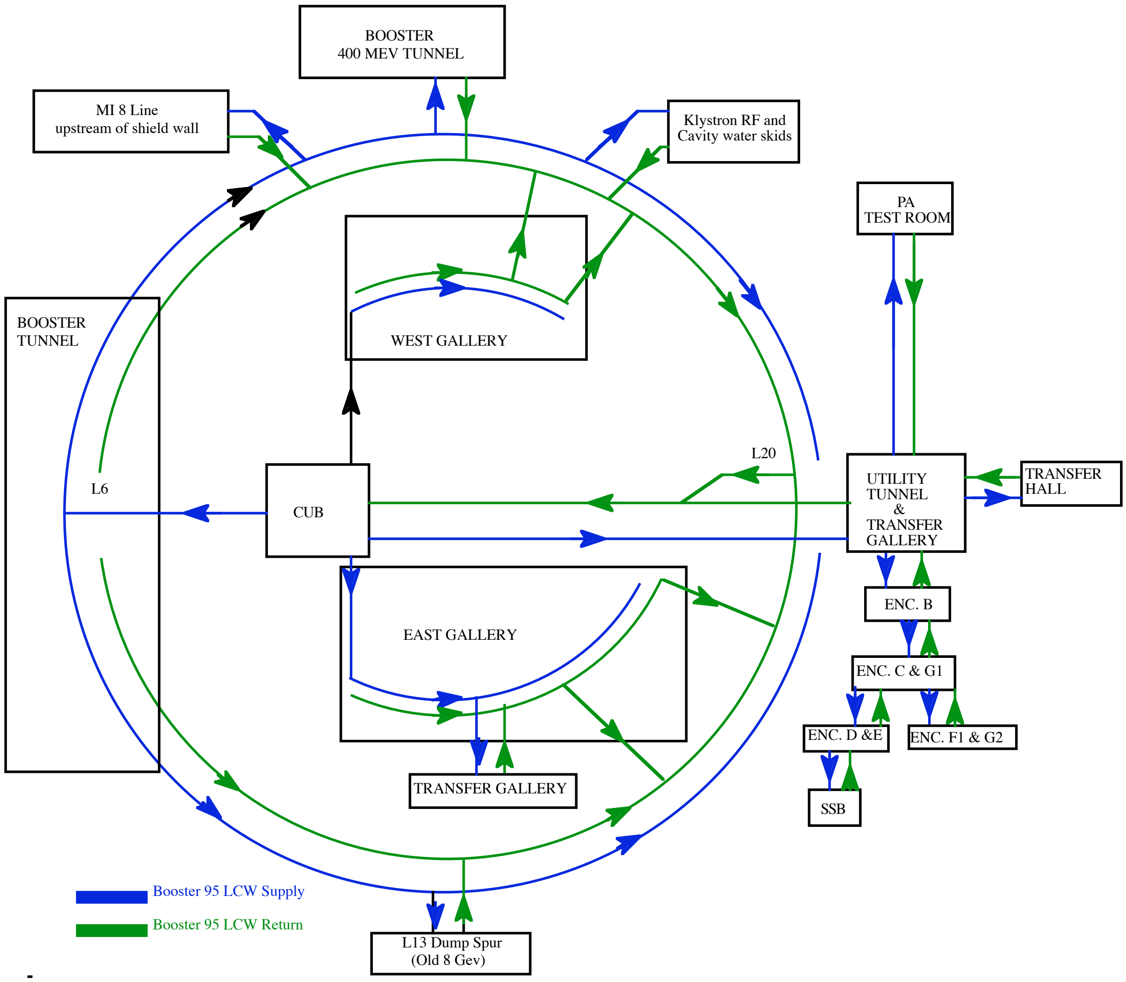


figure 5.2

There are three major circuits in the Booster 95˚ LCW system. The first circuit cools devices in the tunnel; this includes magnets, chokes, RF Power Amplifiers, and ferrite tuners (figure 5.2 is a typical tunnel LCW layout). LCW flow from CUB is sent in an underground header that enters the Booster enclosure at Long 6, then splits in opposite directions and continues around the ring. The supply and return headers run parallel to each other along the tunnel wall around the Booster tunnel. Loads, such as magnets, receive LCW flow from the supply header, then the LCW continues into the return header. The return header exits the tunnel at Long 20 and returns underground back to CUB. (See figure 5.2)

Temperature, pressure, and conductivity readbacks are sent to the MCR via the control system. The gauge that reads the tunnel LCW parameters is located in period 15 of the East Gallery. LCW from the tunnel is diverted upstairs where instruments generate the signals for the readbacks. The nominal temperature for the Booster 95˚ system is actually only 76˚—if it actually reaches 95˚ then equipment will begin to overheat. An RF “watchdog” trip is generated when the gallery LCW temperature rises above a predetermined level. The nominal supply and return pressures are 115 and 30 psi respectively. The nominal flow at a typical RF modulator and power amplifier is 20 psi. If the flow falls below ~10 psi for the modulator and ~15 psi for the power amplifier, it will cause a flow trip inhibit.

The tunnel circuit also has branches that provide LCW for magnets in the Booster side of the 8-GeV line, the 400-MeV line, and the MI-8 line. Supply and return lines branch off from the main headers at period 12 and sends water to the 8-GeV line magnets upstream of the shielding wall. Separate branches service the 400 MeV line magnets in the Booster tunnel and the 400-MeV line quadrupoles in the chute from LINAC, connecting at Long 23 and 22 respectively. The MI-8 line is fed from Long 3, where both supply and return lines are piped overhead at ceiling height.

The second of the three major circuits provides LCW for the power supplies in the West Gallery. The supply header enters the gallery from CUB at period 3, then runs along the wall in both directions. The return header also runs the length of the gallery adjacent to the supply header. The return flow is sent into the tunnel at Long straights 22 and 23 where it connects to the tunnel return header. There are several locations in the gallery where LCW pressure, temperature, and conductivity can be read. Instrumentation at period 23 provides readbacks in the MCR via the control system for those parameters.

The final major circuit of the LCW system provides cooling water for power supplies in the East Gallery. The supply header enters the gallery from CUB at period 11, then runs along the wall parallel with the return header. The circuit also has a branch originating at period 12 that provides LCW for 8-GeV line power supplies. The return header for the gallery is sent down to the tunnel return header at Long 15. As with the West Gallery, there are several locations in the gallery where pressure, temperature, and conductivity can be read locally. The East Gallery has only pressure readbacks via the control system; temperature and conductivity readbacks are not available.

The anode supplies in both galleries have closed glycol cooling systems which heat exchange with the Booster 95˚ LCW system. Glycol is used because the anode supplies are located outdoors and the LCW would freeze during cold weather. The heat exchangers can be found along the outer wall adjacent to the utility yards in both galleries.

Magnet and Cavity Leaks

Valving out a leaky Booster magnet is a major undertaking. In order to isolate one magnet from the 95° LCW system, you are required to valve off each of the magnets around the entire Booster ring. Each magnet has a supply and return valve, plus at Long 3, MP02 is supplied with water and must have either its supply or return valve closed. So that means there are three valves to close at Long 3. And at Long 6 have there's an added return valve, since this is where the bus stops. Remember to always shut the supply valve off first and then the return valve.

Isolating a leaky RF cavity is easier. Simply shut off its supply and return valves.

55° LCW System

The 55° LCW system, used primarily in LINAC, has a circuit in the Booster tunnel. It cools the Debuncher Klystron station and RF cavity in the tunnel. (This system was once used cool the turbo pumps for the vacuum system, but is no longer used for this purpose.) The circuit is fed into the tunnel at Long 6 where it separates into both directions. The return headers exit the tunnel at Longs 17 and 20, then returns to CUB.

Vacuum

In the Booster, as in other accelerators, the beam aperture must be kept at high vacuum to prevent beam loss. If the proton beam strikes gas molecules, part the beam will be scattered and some particles will strike the aperture. The Booster is somewhat unique in that the entire magnet assembly is kept under vacuum. This scheme had already been successfully implemented on one of the Cornell accelerators. Most accelerators have a separate vacuum chamber incorporated into the magnet structure. The main motivation for keeping the entire magnet under vacuum was economic. A thick wall vacuum chamber could not be used due to the large eddy currents that would be induced since the Booster operates at 15 Hz. Wall thickness would have to be very thin, about .005 inch, to avoid the eddy problem. A metal chamber with walls this thin would require a supporting mechanism to prevent it from collapsing. Ceramic vacuum chambers were considered, but would have been expensive and would have substantially reduced the beam aperture. This led to the design of a magnet assembly without a separate vacuum chamber. Also it was found that leaving out the vacuum chamber reduced the amount of energy stored in the magnetic field. This resulted in substantial cost savings for the power supply system, and the capacitors and chokes used in the magnet girder.

The magnet coil and steel laminations for the Booster magnets are enclosed within a vacuum tight stainless steel skin. The entire assembly is formed into a single monolithic structure which requires no outer structural support other than that provided by the thin stainless steel container (see figure 6.1). The laminations are impregnated with heat-cured epoxy resin. The outer stainless envelope provides protection against leaks through the stack of laminations. After being assembled, the magnets were outgassed by baking them out to 150 ˚F under vacuum for nearly two weeks.

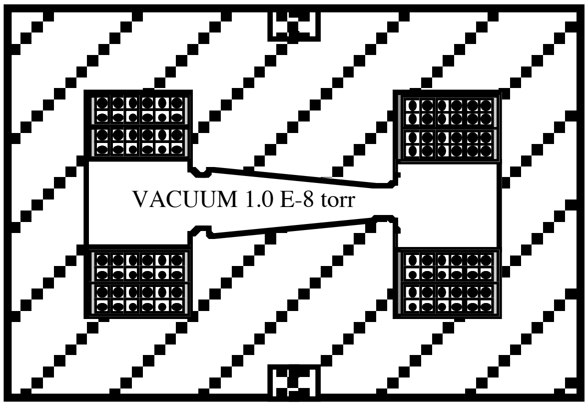


figure 6.1

The Booster ring is divided into eight vacuum sectors, each sealed off from the others by pressurized air "gate valves" (the old system used nitrogen gas). There are four roughing stations, two in each equipment gallery that singly or in combination can rough down any portion of the ring. Each station consists of an 88-CFM (Cubic Feet per Minute) oil sealed rotary mechanical pump and a 157-CFM Roots blower. The blower automatically starts up when the rotary pump has evacuated the system to about 2 Torr. Atmospheric pressure is around 760 Torr.

The roughing pumps are located in the equipment galleries and can be connected directly to the high vacuum chamber in the tunnel by 3-inch diameter pipes, or to the forelines connected to turbo pumps. High vacuum pumping is provided by 600 l/s (liter/second) ion pumps, one on each girder. These lower the pressure to the normal operating range of 1 x 10^{-7} Torr (see figure 6.2). Additional ion pumps are located at each long straight section containing RF cavities, and at the injection and extraction long straights.

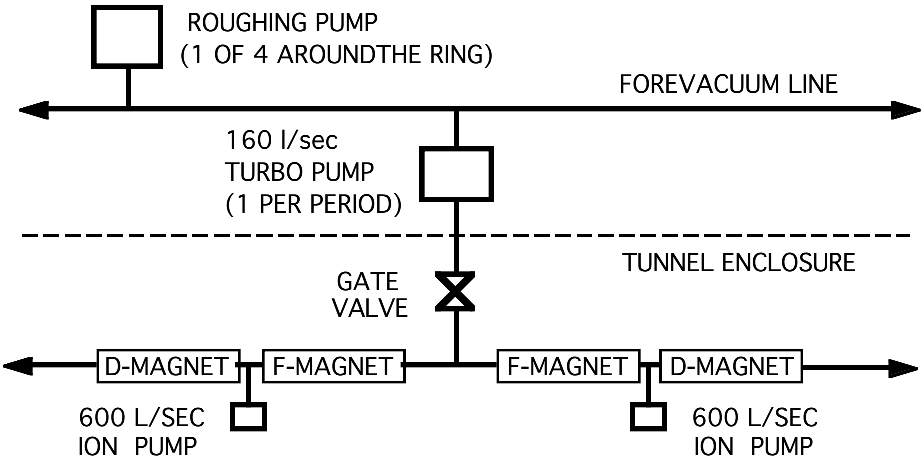


figure 6.2

The intermediate stage pumping is accomplished by 160 l/s Welch turbomolecular pumps. Both the roughing and turbo pumps are off during normal operation, with only the ion pumps maintaining the high vacuum. The system is pumped down from 200 microns to about 5 x 10^{-5} Torr before activating the ion pumps. The turbomolecular pumps also provide additional high vacuum pumping when needed.

All of the turbo pumps in each vacuum sector are commonly linked through a two inch forevacuum line. The forevacuum lines connect to one of the four roughing stations located at each corner of the two equipment galleries above the Booster tunnel.

The 400 MeV line has its own vacuum system (see figure 6.3), with several roughing and turbo pumps located along its length. These are manually operated, so in case of a vacuum problem, an access must be made into the Booster tunnel to open valves and start pumps.

During normal operation, ion pumps maintain a high vacuum in the line. There are four vacuum sectors in the line, each sealed off by valves:

1. from Klystron module 7 to the extraction Lambertson
2. from the Lambertson to Q5 near the top of the chute
3. from Q5 to the Debuncher
4. and from the Debuncher to the MI-8

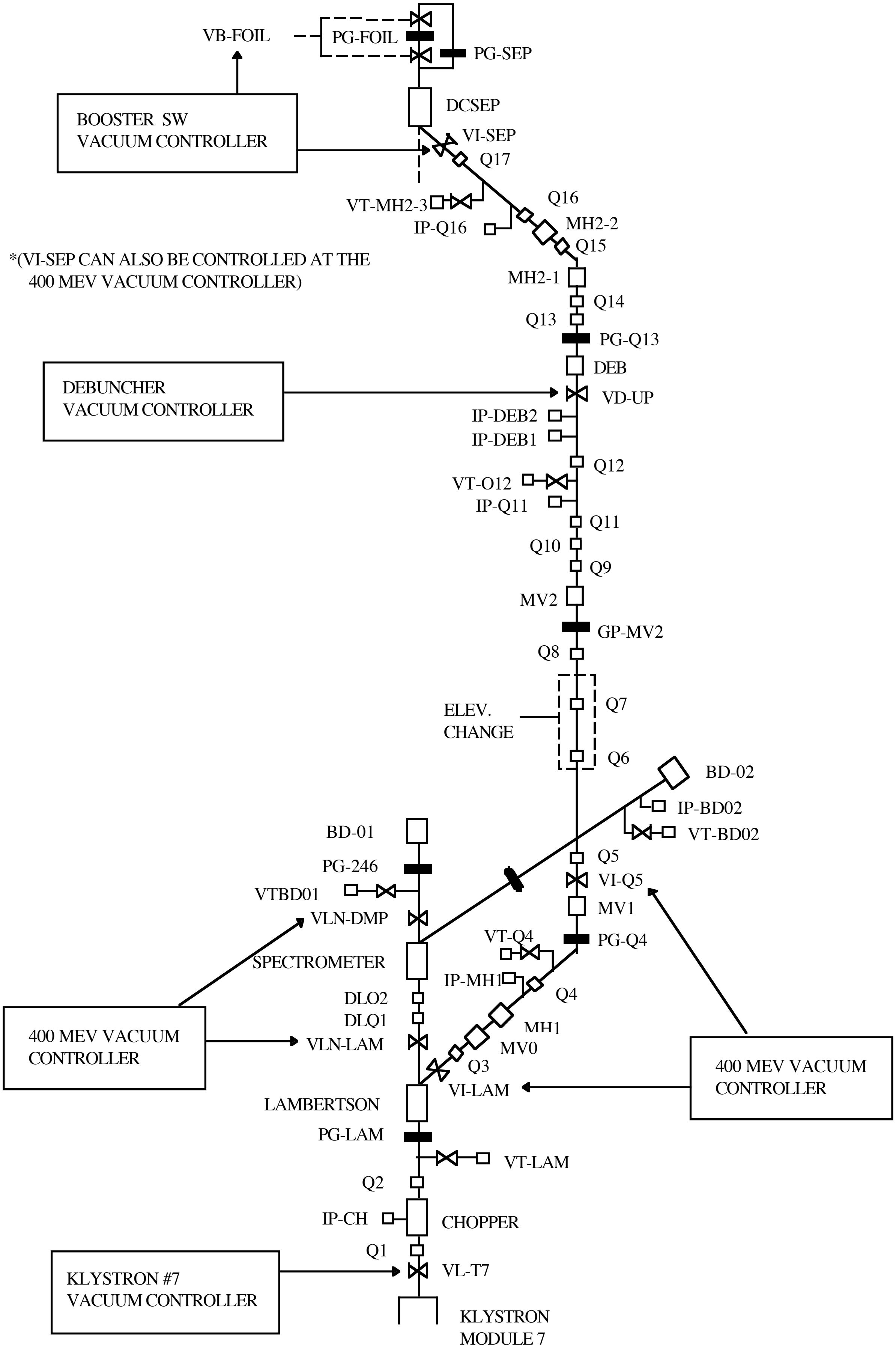

VB-FOIL
PG-FOIL
PG-SEP
BOOSTER SW
VACUUM CONTROLLER
DCSEP
VI-SEP
Q17
VT-MH2-3
Q16
IP-Q16
MH2-2
Q15
*(VI-SEP CAN ALSO BE CONTROLLED AT THE
400 MEV VACUUM CONTROLLER)
MH2-1
Q14
Q13
PG-Q13
DEB
DEBUNCHER
VACUUM CONTROLLER
VD-UP
IP-DEB2
IP-DEB1
Q12
VT-O12
IP-Q11
Q11
Q10
Q9
MV2
GP-MV2
Q8
ELEV.
CHANGE
Q7
Q6
BD-02
IP-BD02
VT-BD02
BD-01
PG-246
VTBD01
VLN-DMP
Q5
VI-Q5
MV1
PG-Q4
VT-Q4
SPECTROMETER
IP-MH1
Q4
DLO2
DLQ1
MH1
400 MEV VACUUM
CONTROLLER
VLN-LAM
MV0
Q3
VI-LAM
400 MEV VACUUM
CONTROLLER
LAMBERTSON
PG-LAM
VT-LAM
Q2
IP-CH
CHOPPER
Q1
KLYSTRON #7
VACUUM CONTROLLER
VL-T7
KLYSTRON
MODULE 7

figure 6.3

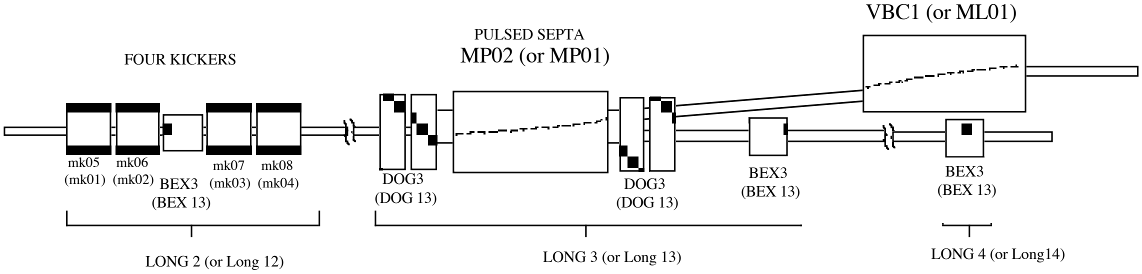
Extraction

The extraction of beam from Booster to the Main Injector occurs at the long 3 straight section. The extraction process uses a kicker and septum combination (see long 3 extraction diagram).

The beam is extracted vertically and is accomplished in one turn by “fast” extraction kickers. Pulsed kicker magnets at long straight 2 give the beam its initial upward push. There are four kickers at long 2. Firing these kickers displaces the beam upward about 25 mm. before the beam reaches the septum at the next long straight section. A total of four kickers must be fired to provide the necessary displacement. The kickers have a rise time of approximately 30 nsec which means that at least one bunch is lost during the extraction process. (Remember that the beam injected from LINAC completely fills the Booster ring. When the extraction kickers fire, part of the beam receives only a partial kick and does not get displaced enough to reach the field region of the extraction septum (see figure 7.1). The time interval between bunches is about 19 nsec.

L3 or (L13) Extraction

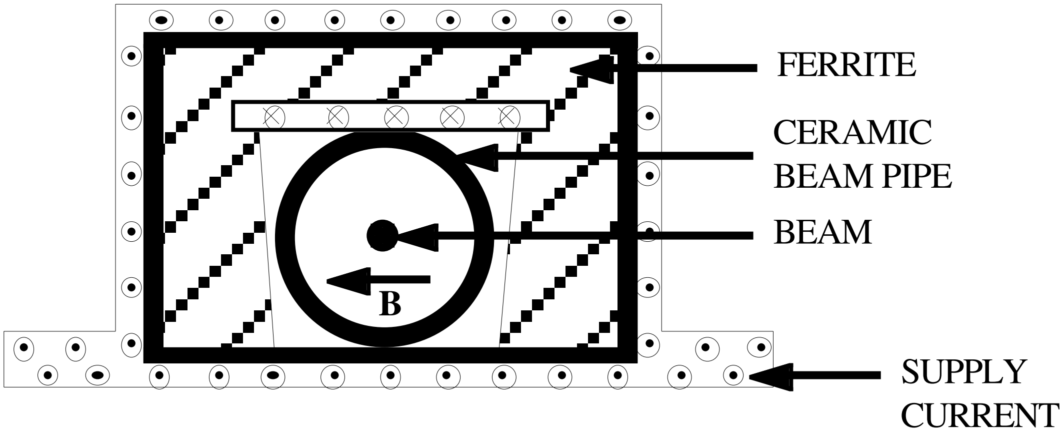
L3 and L13 extraction are very similar. L3 extraction is shown below, with the equivalent L13 extraction shown in parenthesis.



1. DOG 3 (DOG13) is a four bump (double dogleg) that bends injected beam down away from the septa plate.
2. As beam increases in energy, beam size shrinks and the affect of the dogleg decreases. The net effect of this is the top edge of the beam stays close to the lower edge of the septa plate.
3. BEX 3 (BEX13) is a ramped three bump that is used around extraction time to raise the beam closer to the septa plate
4. At extraction time, the kickers are fired. The kickers deflect beam upward.
5. The kicked beam goes above the septa plate in MP02 (or MP01). MP01 then further bends the beam up and out of the Booster into the MI-8 line (L13 dump)

figure 7.1

The extracted beam requires a stronger vertical bend to clear the upstream ring magnets in the next period. The pulsed magnetic septa magnets MP02 at long 3 (and MP01 at long 13) provide that bend. The upward vertical displacement provided by the kickers places the beam in the field region of the septum. The septum then bends the beam an additional 44 milliradians, enough for the extraction line to clear the gradient magnets downstream of the septum magnet. Kicker and septum combinations are used in all of the accelerators for injection and extraction. Kickers have the advantage of being fast and not having an aperture restriction, but a disadvantage of providing only a small bend angle to the beam (see booster kicker face diagram 7.2). Septum magnets have a much stronger field, but require a septum plate to separate the field region from the field-free region that circulating beam passes through.

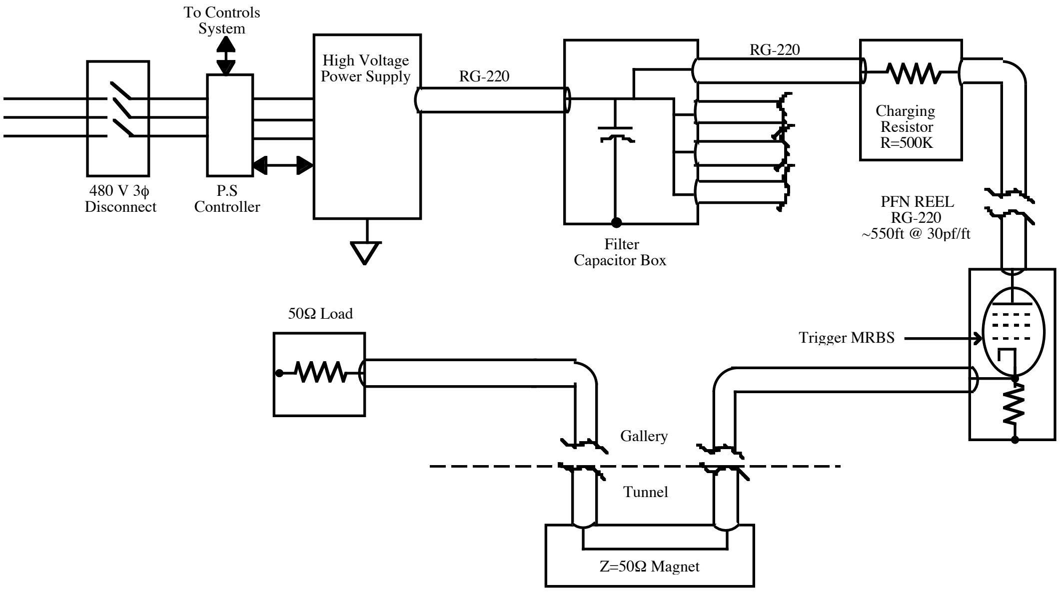


Booster Kicker Face diagram

figure 7.2

What follows is a brief outline on the placement and power supply arrangement for the kickers. There are eight kicker power supplies that power mk01-mk08. Four of the kicker magnets are located in the long 2 straight section, MK05, MK06, MK07, and MK08. And four magnets are located in the long 12 straight section: MK01, MK02, MK03 and MK04. (See figure 7.3 for typical layout.) Each kicker is associated with a single magnetic element in the tunnel.

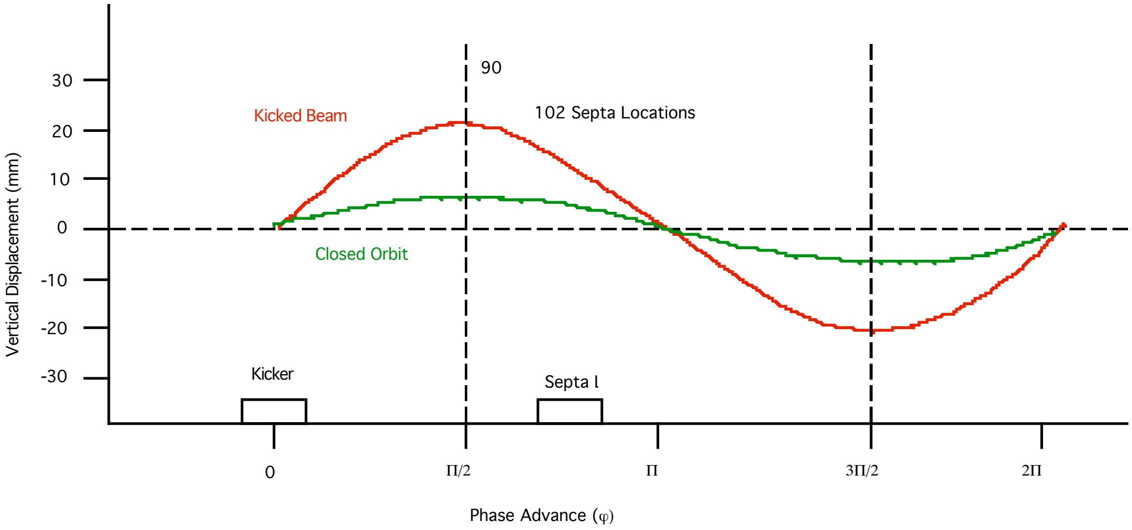
Each of the eight kicker elements delivers approximately a 1.05 E-03 mm/KV kick. At nominal voltage, this results in a bend angle of a bit over 1 milliradian when four kickers are fired together. Calculating beam displacement in an accelerator with a bend angle, must include lattice parameters such as the beta function and the betatron phase advance. Since the beam undergoes betatron oscillations, the placement of the kickers and septa in the accelerators is very important. A transfer function determines what angle is required at the kicker to obtain the necessary displacement at the septa.



Booster Kicker Diagram
figure 7.3

For the Booster, the orbit of the circulating beam is located about 10 mm. below the septa plate. If we want to kick the beam into the center of the field region of the septum magnet, we need about a 30 mm. vertical displacement. By spacing the kicker and septum one period apart, the beam undergoes a betatron phase advance of 102° (the beam undergoes about 6.8 betatron oscillations, which is the same as the tune, over 24 periods as shown in figure 7.4). The beam's maximum displacement is at 90° and 270°, so a reasonable arrangement would place the kicker and septum one period apart. In the case of Booster, you are not getting the peak displacement at the septum. Note that it is possible to create an arrangement (like when the phase advance is 270°) where a kick in one direction would result in a displacement in the other direction. (See Booster Phase Advance Diagram, 7.4)

The booster extraction kicker power supplies have voltages that run in the 55-60 kV range. Any four of the eight kicker elements may be used together to produce the necessary displacement. Typically, MK01, MK02, MK03 and MK04 are fired together when extracting to the dump at long 13, and MK05, MK06, MK07, and MK08 are used when extracting to the Main Injector at long 3.

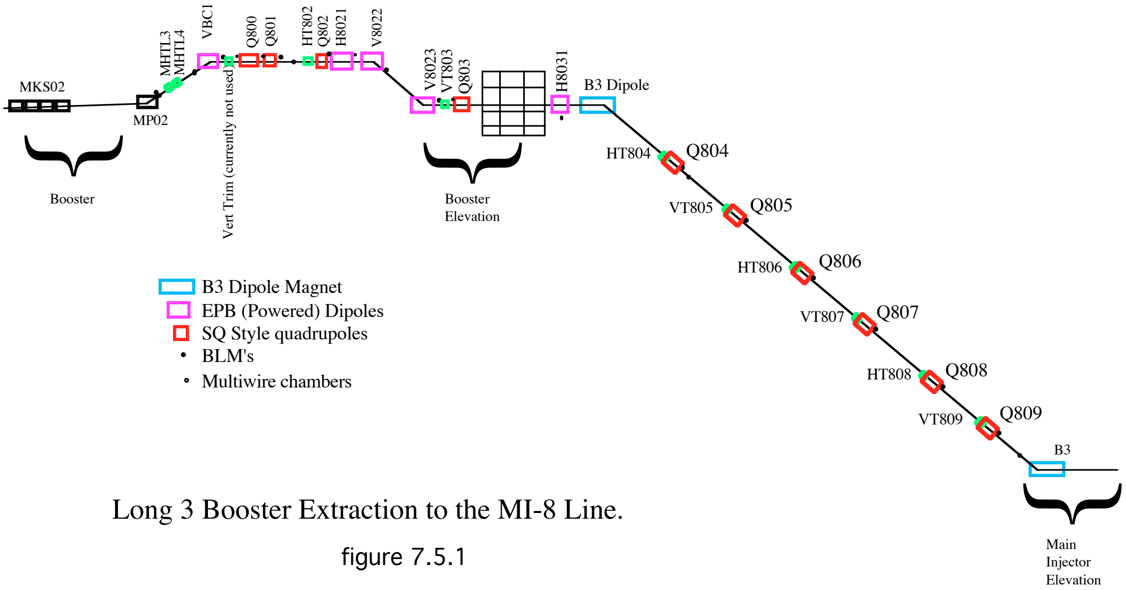


Booster Phase Advance Diagram

figure 7.4

MIBS and “Tauser” modules control the timing of the individual kickers. The Tauser modules, which are RF counters, delay the firing of the kickers until after an extraction timing pulse is generated. By using appropriate delays, bunches can be delivered to the Main Injector, the dump, or a combination of the two. This is how you accomplish “short batching” into the Main Injector during Collider mode. The Main Injector receives a limited number of bunches while the rest go to the Booster 8 GeV dump.

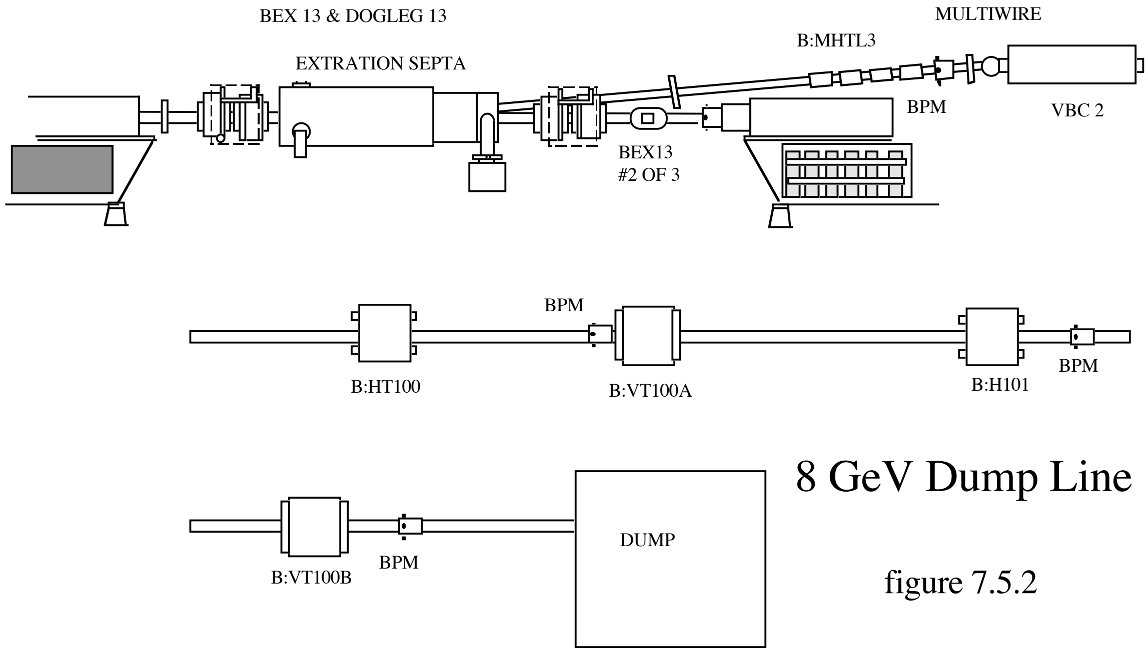
With beam extracted to the Main Injector, there is a separate vertical magnet used to provide the down-bend to offset the upward angle created by MP02. The vertical magnet is B:VBC1 (Vertical Bend Center 1), a Pbar beam line style dipole. Different power supplies power B:MP02 and B:VBC1; MP02 is pulsed and VBC1 is run DC. These supplies are necessary for the MI8 extraction. This is the reason why they are critical devices for MI8/MI. (see figure 7.5.1)



Long 3 Booster Extraction to the MI-8 Line.

figure 7.5.1

In the case of extraction to the dump, the beam is bent upwards by B:MP01. An inflector magnet, ML01 is used to straighten the beam out, parallel to the Booster centerline. MP01 and ML01 are connected in series and powered by the same capacitor-discharge power supply. ML01 is just an upside-down MP01, with the dump beam going through the bottom (field) section of the magnet (see figure 7.5.2).



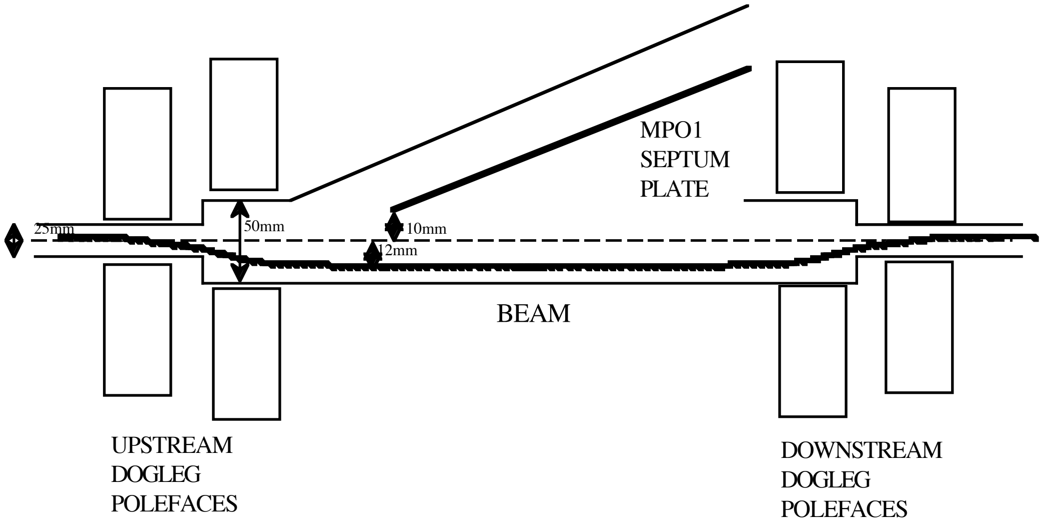
8 GeV Dump Line

figure 7.5.2

The vertical apertures in the extraction areas require special attention. The septa plate lies close to the vertical centerline (approximately 10 mm. above). Since the vertical aperture in the F gradient magnets is about 50 mm., this leaves only ~35 mm. for beam to occupy during injection and acceleration. To keep from losing beam on the septum during acceleration, two separate devices are used.

"Bexbump," the first of these devices, is a ramped vertical 3-bump with magnets located in the 2, 3, and 4 long straight sections (there is also a Bexbump at periods 12, 13, and 14 for long 13 extraction). These magnets are air core trim dipoles, like some of the trims in the 400 MeV line, and are ramped via 465 modules. At extraction the bump is ramped positive to bring the beam closer to the septum plate and reduce the required kick; the beam size shrinks as the energy increases—injected beam is significantly larger than extracted beam. (The benefit of using dipoles is accurate position control through the entire cycle, keeping beam far enough below the septum to prevent beam loss.)

The second device is the "double dogleg" a group of four vertical dipoles arranged as two sets of two magnets just upstream and just downstream of MP02 and MP01. These sets are doglegs operating in opposite directions. The first dogleg bends beam down and then straightens the beam parallel to, but about 12 millimeters below, the Booster centerline. The second set of dogleg magnets reverses the process and bends beam back up to the normal closed orbit (see figure 7.6). Since these magnets are operated DC, the magnitude of the bump decreases as the momentum of the beam increases. The magnitude of the bump is proportional to 1/p, but the beam size decreases as $p^{-1/2}$. Since the bump is primarily needed early in the cycle when the beam is large, it made sense to run the magnets DC.



Booster Extraction Region

figure 7.6

Diagnostics

The operation of the Booster, or any other accelerator, could not be possible without beam diagnostics. Other machines contain many of the various forms of Booster instrumentation and diagnostics described in this section; only a few devices are unique to the Booster. There are a number of ways to measure the beam parameters of interest, but they are always in a state of flux and the details are adjusted to fit the present running conditions.

Multiwires

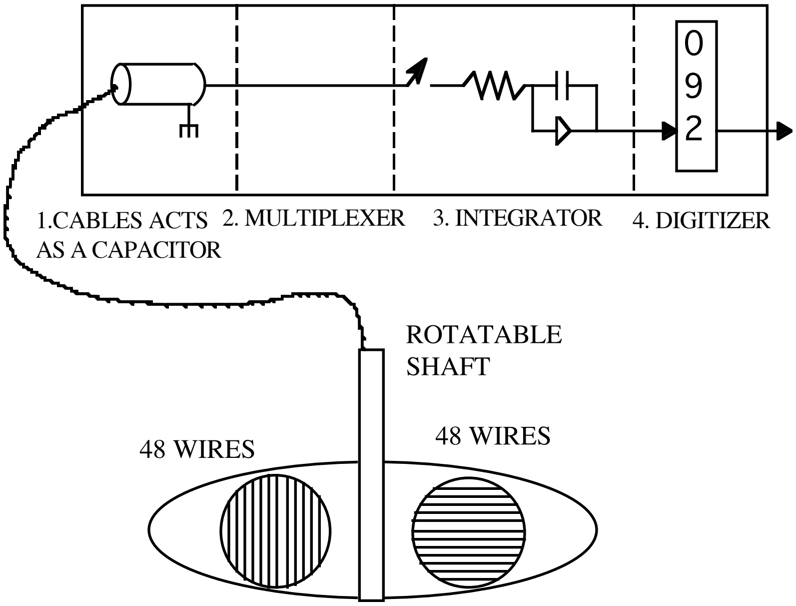


figure 8.1

The Booster multiwires are used to measure beam profiles. Since the multiwires are intended to be used with a single pass of beam, their use is restricted to the 400 MeV line and 8 GeV line. The multiwire hardware in the tunnel consists of a propeller-like paddle attached to a vertical rotatable shaft and two sets of wires, one on either side of the paddle blades (see figure 8.1). One side of the blade has 48 wires positioned horizontally, and the other side has 48 wires positioned vertically (there are actually only 48 wires total, as each horizontal wire is in series with a corresponding vertical wire). The wires are spaced one millimeter apart in both planes. Either side of the paddle may be rotated into the beam, depending on whether a vertical profile or horizontal profile is desired (figure 8.2). Beam passes through the plane of wires at right angles and generates a current in the wires. The amount of current induced in each wire is a measure of the beam's intensity at that point. All of the wires taken together yield a profile of the beam in that particular plane.

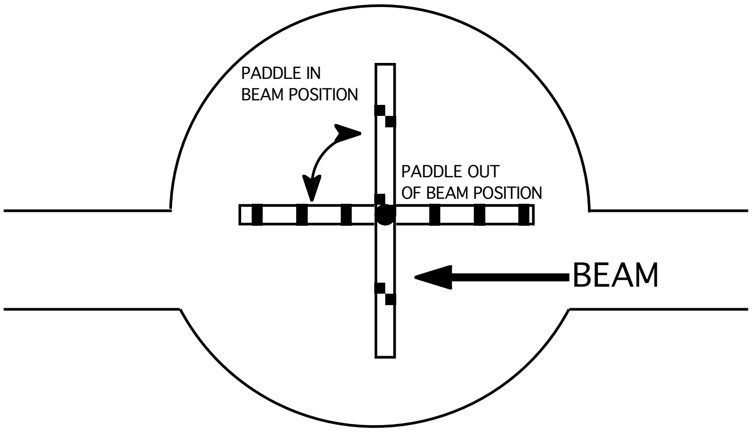


figure 8.2

The generated signal is directed by cable to a RF module upstairs, with the cable acting as a capacitor and storing the induced charge. All 48 wires go into a multiplexer (to select which wires are being looked at), through an integrator (to look at the total charge induced), and then to a multiwire digitizer card located in a CAMAC crate. The signal coming out of the digitizer card passes through the crate controller and then relayed to the Booster front end. Signal scaling is performed in the database.

Crawling wires

The Booster crawling wires, which are similar to the flying wires found in other accelerators, measures the profile of circulating beam. They are an automated profile measuring system using single wires scanners, capable of measuring the profile on a turn by turn basis. More than 30 profiles can be accumulated before the wire significantly degrades the beam. The crawling wires are located near the injection girder and also at long straight sections 3 and 10. There are a total of four horizontal and four vertical crawling wires in the Booster.

The crawling wire hardware in the tunnel consists of a fork with a single tungsten wire, 5 mils thick, connecting the two prongs (see figure 8.3). A stepping motor capable of stepping the wire in sub-millimeter increments controls the wire position. The raw wire data is sent through a 1 MHz filter and amplified before being input to a fast digitizing Gould scope. The scope is read out through a GPIB interface and sent to the Booster front-end computer. The front end then transfers the data into a filesharing utility on the VAX.

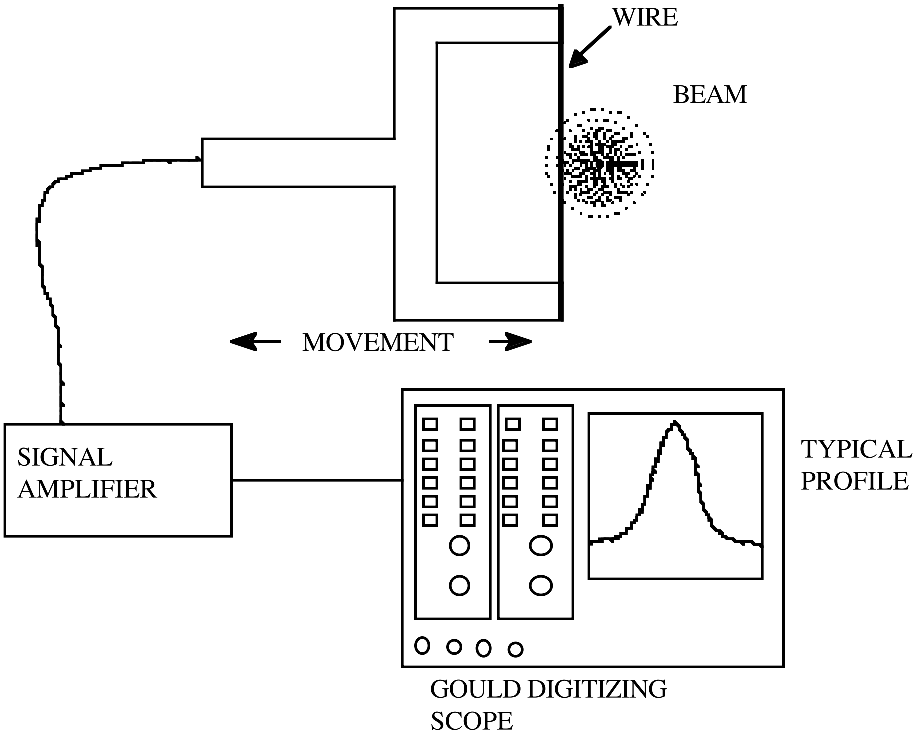


figure 8.3

A crawling wire display has intensity on the vertical axis and position on the horizontal axis. Such a profile is obtained by passing the wire through circulating beam, which sets up a current on the wire. The current on the wire is read at selected time intervals within the beam cycle, advancing the wire to different positions and recording the same information on subsequent beam pulses. A crawling wire display often has a series of profiles staggered vertically, each representing a different time in the cycle. For thin wires, the losses on a turn by turn basis are small and readily calculable. A more serious limitation than wire losses on the data analysis is the pulse to pulse stability of the beam.

A second application of these wires has allowed a view into the internal properties of the beam pulse. By setting the time interval at which the wire readout occurs to a fraction of the total time span of a beam pulse, the individual profiles generated represent a particular time in the beam pulse. This is a way to study the intensity and position variations within a beam pulse.

Beam Position Monitors

The Booster Beam Position Monitors (BPM's) measure both vertical and horizontal beam positions as well as beam intensity. The BPM detector is an impedance matched stripline device consisting of four striplines contained in a single cylindrical housing which allows measurements in both planes at a single location (see Figures 8.4 & 8.5).

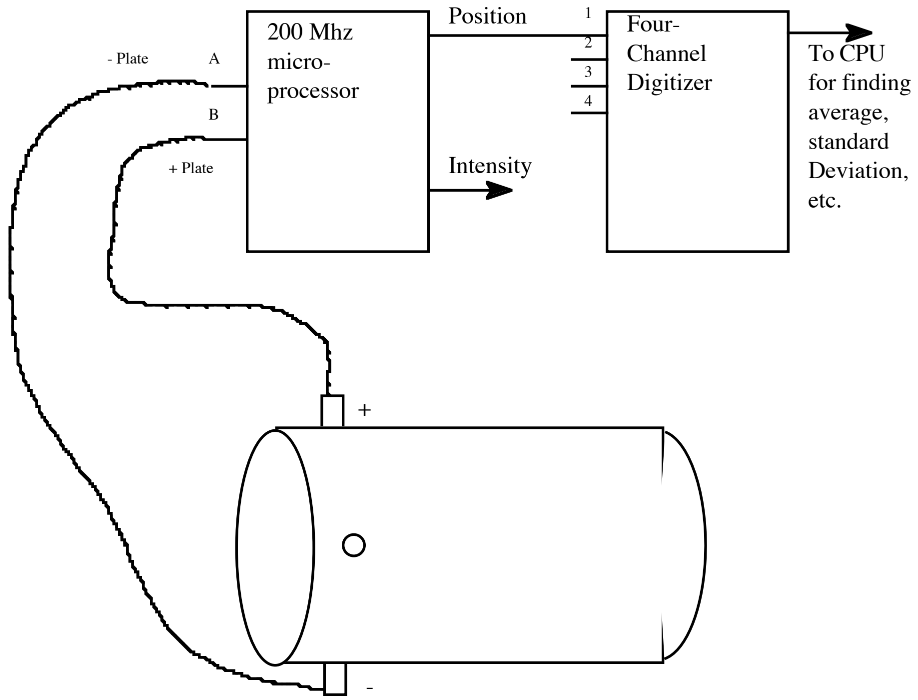


figure 8.4

Each 50Ω stripline detector is a section of a circle subtending an arc of 60 degrees and measuring 6 inches long (see Figure 8.5), and is sensitive in the direction of beam travel. The detector's downstream ends are terminated in vacuum and only signals from the upstream end are available.

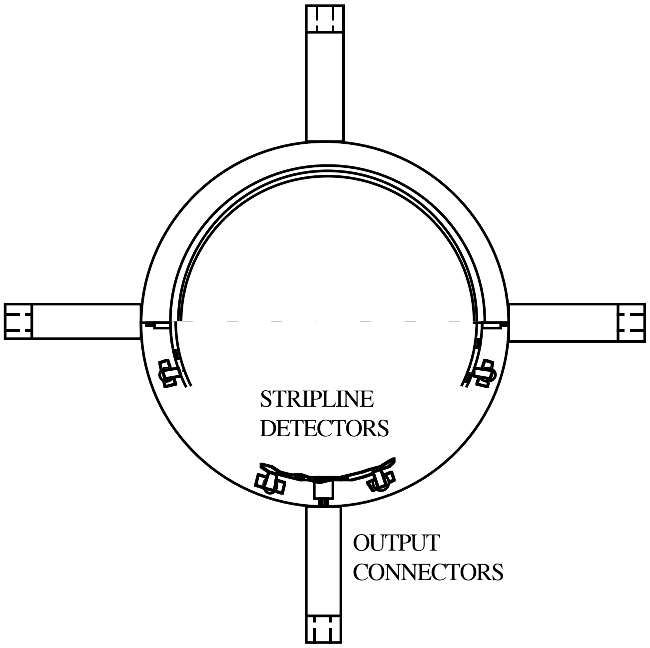


figure 8.5

The stripline detectors each run along the inside length of the cylinder. As beam passes through the center of the cylinder (inside the cylinder and parallel to its length), it sets up charges in the four detectors. The signals from the top and bottom detectors are used for determining vertical beam position, with the signals from the left and right detectors are used for determining horizontal beam position.

Each of these pairs of signals are sent upstairs (see figure 8.4), where the signals pass into a 200 MHz microprocessor that performs averaging and scaling of the position signals. Unlike the other BPM systems at Fermilab, the scaling of the position signals, as well as averaging and offsets, is done locally in the microprocessor. Also, the Booster BPM system has no analog box like the BPM systems for the Main Injector and Tevatron.

The output of the microprocessor goes into a four channel digitizer located in a VME crate, where the position and intensities are digitized at a 5 MHz rate during the beam pulse. Since the length of the beam pulse varies, depending on the number of turns injected into the Booster (a single turn of Booster beam requires a 2.8 µsec pulse), the digitizer must be told when to gate on and off. This is done using a gate generator pulse that is derived from the 400 MeV chopper (B:CHOP) power supply trigger and conditioned by intensity. In this way, the beam position is monitored for the entire length of the beam pulse no matter how many turns are injected into Booster. The falling edge of the gate signal generates a VME interrupt, causing the digitized data to be read. The output of the digitizer then goes to a CPU, which calculates average position, position sigma, and average intensity for each beam pulse. The token ring transmits the position information to the accelerator controls system. An application program will display this information in graphical form as well as numerically.

There are 48 BPM's located in the Booster ring, one at every short and long straight section. There are also 26 BPMs in the 400 MeV line. Racks located in the equipment galleries contain all the microprocessors, digitizers, and other electronics. The positions are displayed in map form along with the respective magnets to facilitate tuning of beam position along the line as well as injecting properly into the Booster.

Two VME crates digitize the beam signal. Each crate includes a processor board, system services module, memory board, token ring interface board, universal clock decoder, and several digitizer boards. The system services module is a Fermilab-designed board that includes a bank of dot matrix displays, LED displays, and switches for diagnostic purposes. The switches are also used to set the Token Ring address for the crate. The SSM board has a multifunction peripheral chip that generates interrupts from external signals.

The universal clock decoder is a Fermilab-designed board that decodes Tevatron and beam synch clock events. The on-board state machine is programmed to produce the proper VME bus interrupts in response to clock events. The UCD board also provides process-scheduling interrupts.

The digitizers are four channel, 5 MHz quick digitizer boards designed at Fermilab. The position signals are digitized with 12 bits of resolution and several intensity signals are also digitized. Each digitizer board has 512 Kbytes of memory available that can store 64,000 positions or intensity samples from each detector before overwriting the information.

Ion Profile Monitor

Ion Profile Monitors (IPMs) were first used in the Pbar source, but are now located in Booster at long straight section 4. The monitor is a non-destructive diagnostic tool used to measure the transverse beam size of the circulating beam. When the beam interacts with gas molecules in the beam pipe, ionization takes place. The IPM detects the resultant ionization from this interaction and uses that measurement to correlate between the Booster beam intensity and structure. The system relies on the fact that Booster vacuum is not perfect, that some residual gas remains in the beam pipe. Unfortunately, the IPM performance decreases as vacuum improves.

The present control of the IPM is done through a Labview™ scheme interfaced with the controls system through the database.

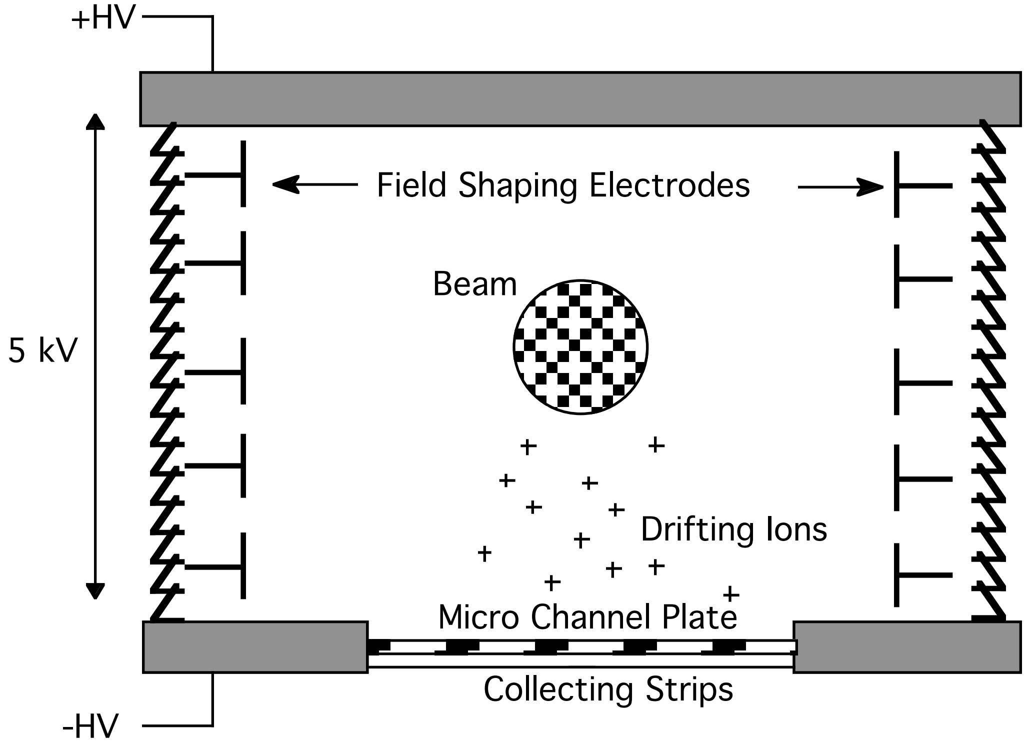
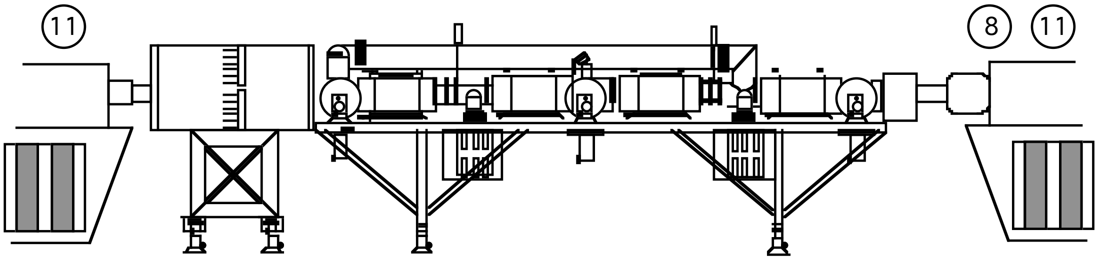


figure 8.6

Booster Device Appendix

1. BPM
2. Ramped Sextupoles
3. RF Cavity
4. Octupoles
5. Toroid
6. Vertical 1 GHz Stripline Detector
7. Horizontal 1 GHz Stripline Detector
8. Correction Element Package
9. Vertical Kicker/Pinger (Studies)
10. Horizontal Kicker/Pinger (Studies)
11. Magnet Girder
12. Emittance Detectors
13. Extraction Kickers MK01, MK02, MK03, & MK04
14. Bex Bump 3 #1
15. Harmonic Sextupoles (1 Normal & 1 Skewed)
16. Crawling Wire
17. Bex Bump 3 #3
18. Bex Bump 13 #3
19. Manual Vacuum Valves
20. Vertical Damper (Super Camper)
21. Longitudinal Damper
22. Damper Pickup
23. Mountain Range Pickup
24. IPM (Ion Profile Monitor)
25. Extraction Kicker MK05, MK06, MK07, & MK08
26. Horizontal Damper
27. Multiwire
28. Vacuum Valve
29. RPOS Detector
30. Resistive Wall Monitor
31. Ion Pump
32. Dog 3 or Dog 13
33. Bex Bump 13 #1
34. MP01 or MP02
35. Bex Bump 3 or Bex Bump 13 #2
36. Collimator

Device Appendix



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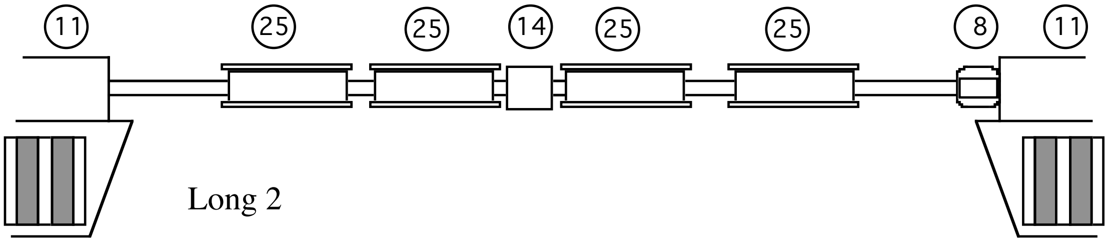

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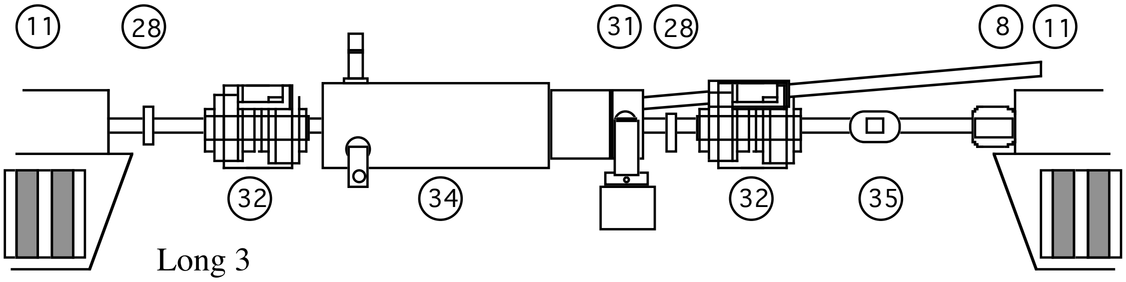

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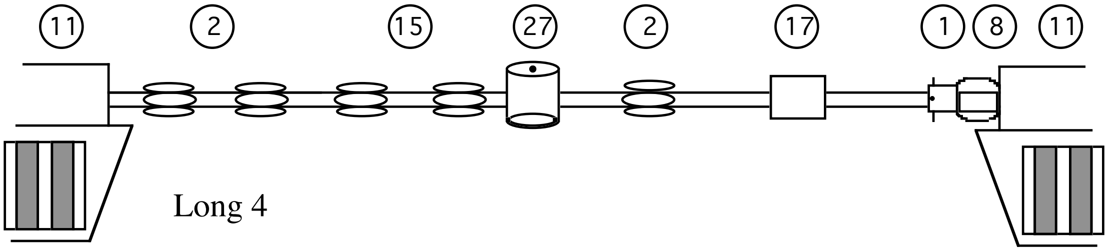
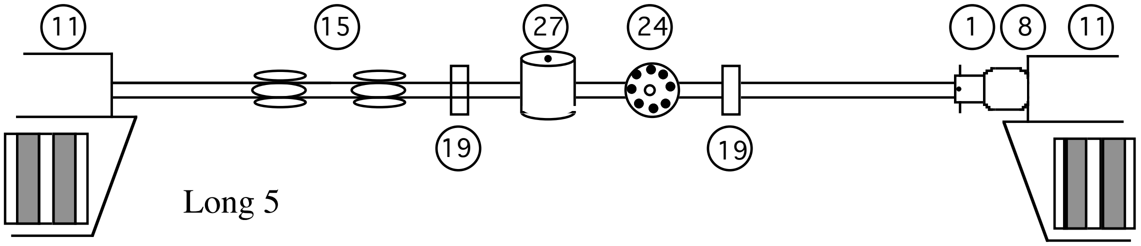


Long 4

Device Appendix



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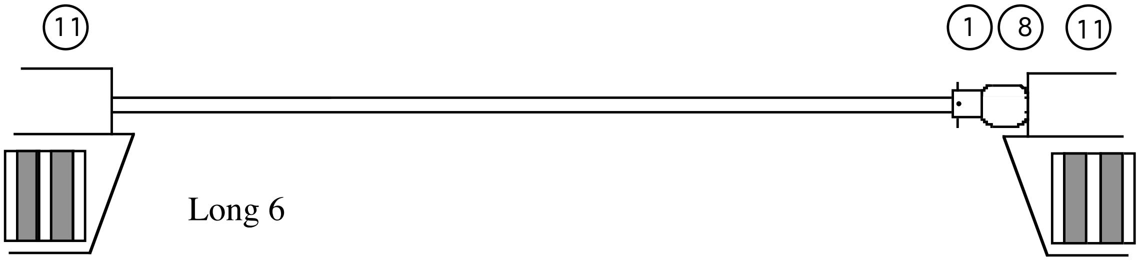

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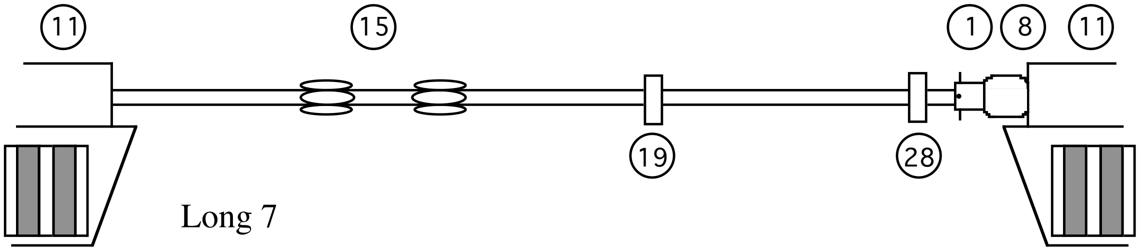

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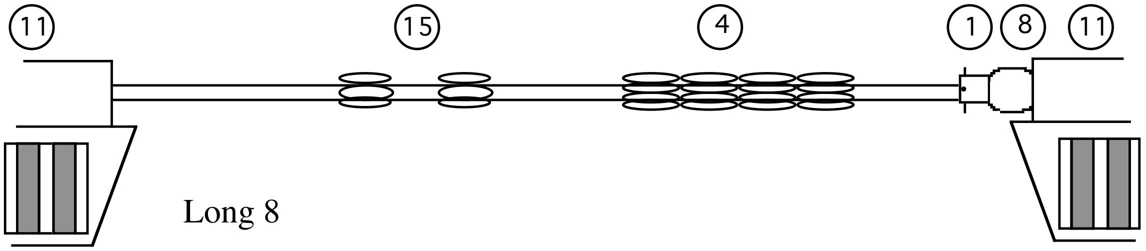
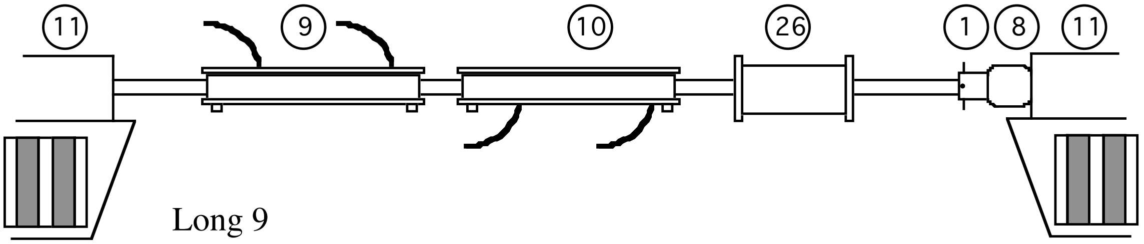


Long 8

Device Appendix



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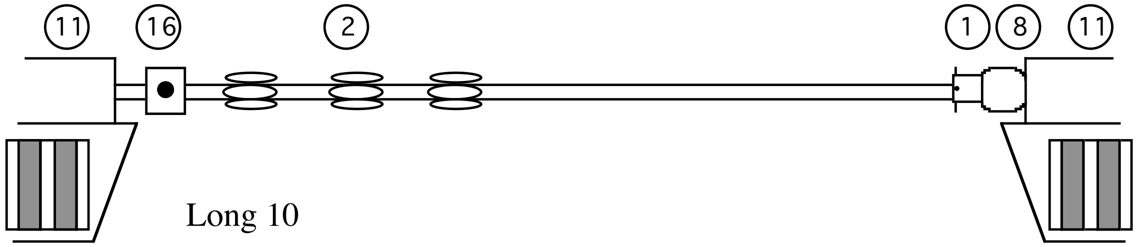

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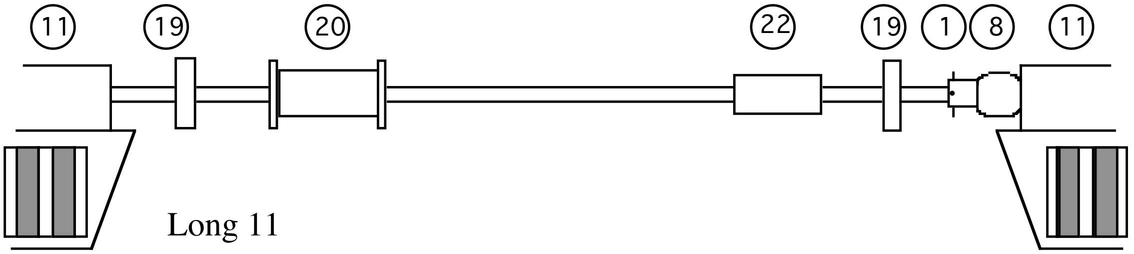
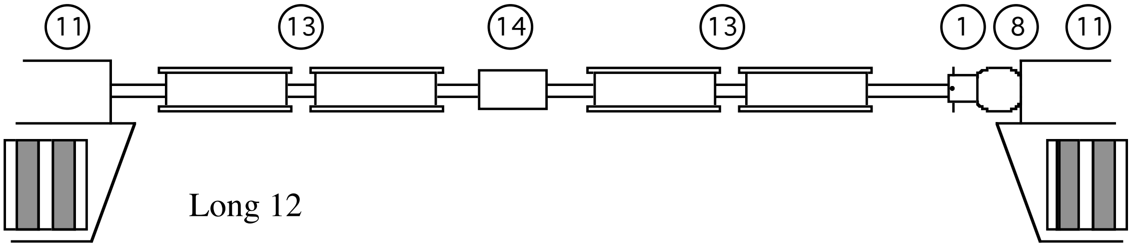
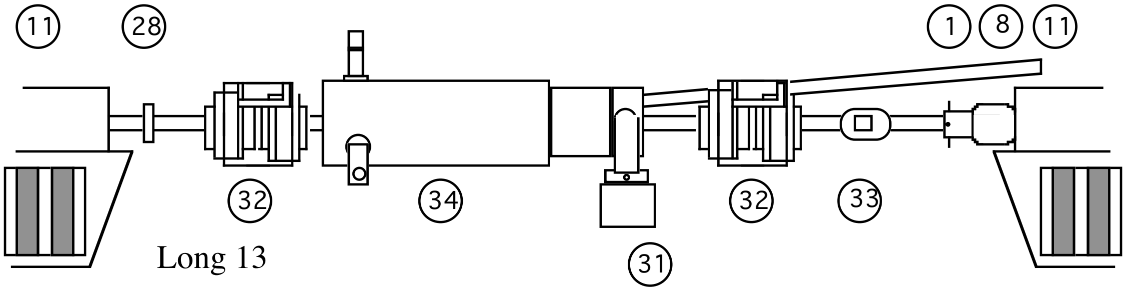


Long 11

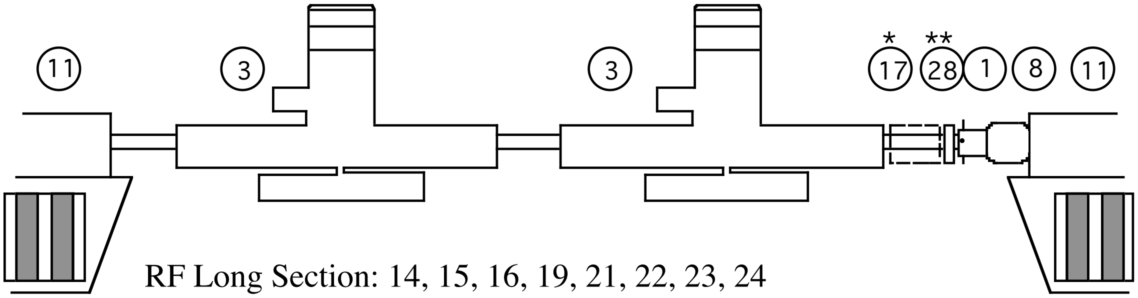


Long 12

Device Appendix

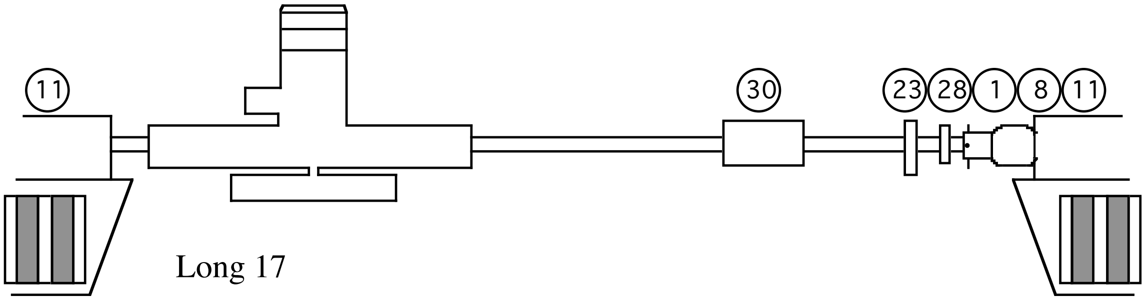


Long 13

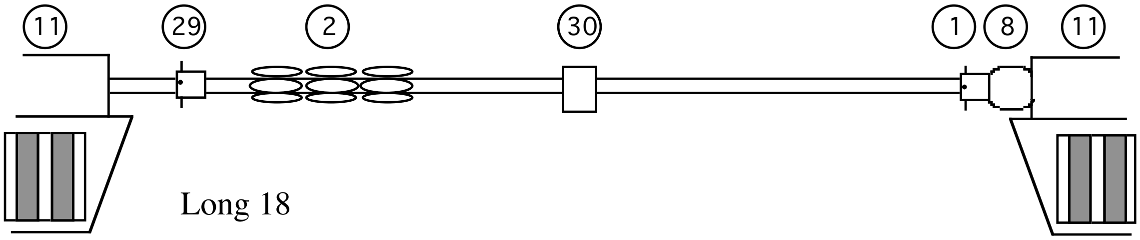


RF Long Section: 14, 15, 16, 19, 21, 22, 23, 24

*3rd BEX Bump only at Long 14
** Vacuum valve prior to BPM at 19, 21, 24

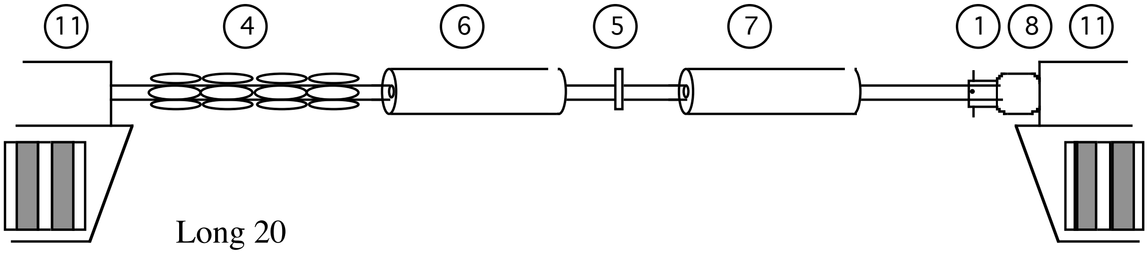


Long 17



Long 18

Device Appendix



Long 20

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Notes: