Chapter 12. Extraction and Abort

Alexandr Drozhdin, Carol J. Johnstone, Jim Lackey and Shoroku Ohnuma

12.1. Introduction

This chapter outlines the 16 GeV extraction system. The extraction system is described in Section 12.2 and the required “notcher” in Section 12.3. In Section 12.4 are discussed the various issues related to an abort system.

The extraction system is designed to extract 100% of the beam in one turn. Design of a "slow" extraction system is not part of this study.

Although the design beam normalized emittance is 60 π mm-mrad, apertures of the extraction system elements are designed to maintain clearance for a maximum beam normalized emittance of 120 π mm-mrad at 400 MeV and at 16 GeV. An aperture this large at injection time insures that the collimation system will intercept circulating beam losses and prevent the various extraction elements from becoming radioactive. At 16 GeV an extraction channel aperture as large as reasonably possible is highly desirable since it reduces alignment tolerances and allows the extraction channel to accommodate to some amount of halo on the beam.

The layout of the extraction system in straight section P60 is shown in Figure 12.1.

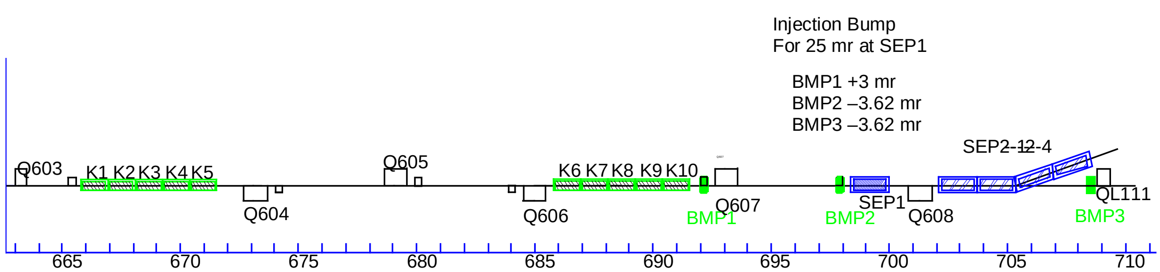

Figure 12.1. Proton Driver Extraction System Layout

12.2. Extraction system

12.2.1. Kickers

In the present lattice design the lattice functions at the kicker locations are not optimal for extraction. The net result is that the number of kicker magnets is larger than the number that a lattice optimized for extraction would require. The apertures of the kickers assume the use of a ceramic beam tube with wall thickness ~5 mm. The kickers will be capacitively loaded ferrite transmission line magnets with a nominal impedance of 12.5 ohms. A current rise time of 125 ns is assumed, giving an effective fill time of ~168 ns.

There are two sets of kickers. The phase advance of the first set is ~240 degrees from Septum 1 and the second set is ~60 degrees. With these phase advances the first set of kickers has to give a negative kick to the beam so that 180 degrees later the kick angle becomes positive and adds to the positive kick of the second set. The horizontal beta function over the length of the kickers varies from near maximum to near minimum so the effective beta is the average for that location. The horizontal beta function at the location of Septum 1 is also quite small. Since kick amplitude at the septum x_2 is given by:

$$x_2 := \sqrt{\beta_1 \cdot \beta_2} \cdot \sin(\psi_{12}) \cdot x'_1$$

the effects of small betas and a 60-degree phase advance necessitate a larger number of kickers. There would be some gain in effective kicker strength if one changed the gap of the individual kicker magnets as the beta function changed, but that was not done in this design.

12.2.2. Septa

The design of the extraction system requires two septum magnets. The first septum (Septum 1) will of necessity be a "thin" septum design. Septum 1 will be a single turn pulsed magnet. The design assumes a maximum 10-mm septum thickness, believed to be sufficient to provide the required mechanical strength, cooling, and magnetic field shielding for the circulating beam. The design gap height is 30 mm and poletip width is 40 mm.

The gap height of 30 mm (1.181") is similar to the existing Booster extraction septum, and the 1.1 Tesla field is also about the same. A 1.5 meter, 15 Hertz extraction septum magnet with a 3-mm septum and nominal field of 1.0 Tesla for the Booster is under construction. It is expected that testing of the design will begin early in 2001. This new magnet is essentially the Septum 1 design. Figure 12.2 shows a cross section of this magnet.

The amplitude of the kicked beam at the upstream end of Septum 1 is given by $W_b + S_t + x_b$. W_b is the beam width, S_t the Septum thickness and x_b the injection bump. With W_b = 20.28 mm, S_t = 10 mm and x_b = 1.5 mm, $W_b + S_t + x_b$ = 31.78 mm.

The extracted beam position at the upstream end of the second septum (Septum 2) is +165 mm (~6.5") outside the circulating beam orbit. This gives sufficient room to consider the use of a dc septum magnet or at least a multi-turn pulsed magnet. In this design it is assumed that Septum 2 will be 4 individual magnets. The gap height of the Septum 2 magnets is 30 mm and the poletip width is 75 mm.

The horizontal beam size at the downstream end of Quad Q608 is at ~137 mm (5.4") so a special vacuum pipe interface between Q608 and Septum 2 will be required.

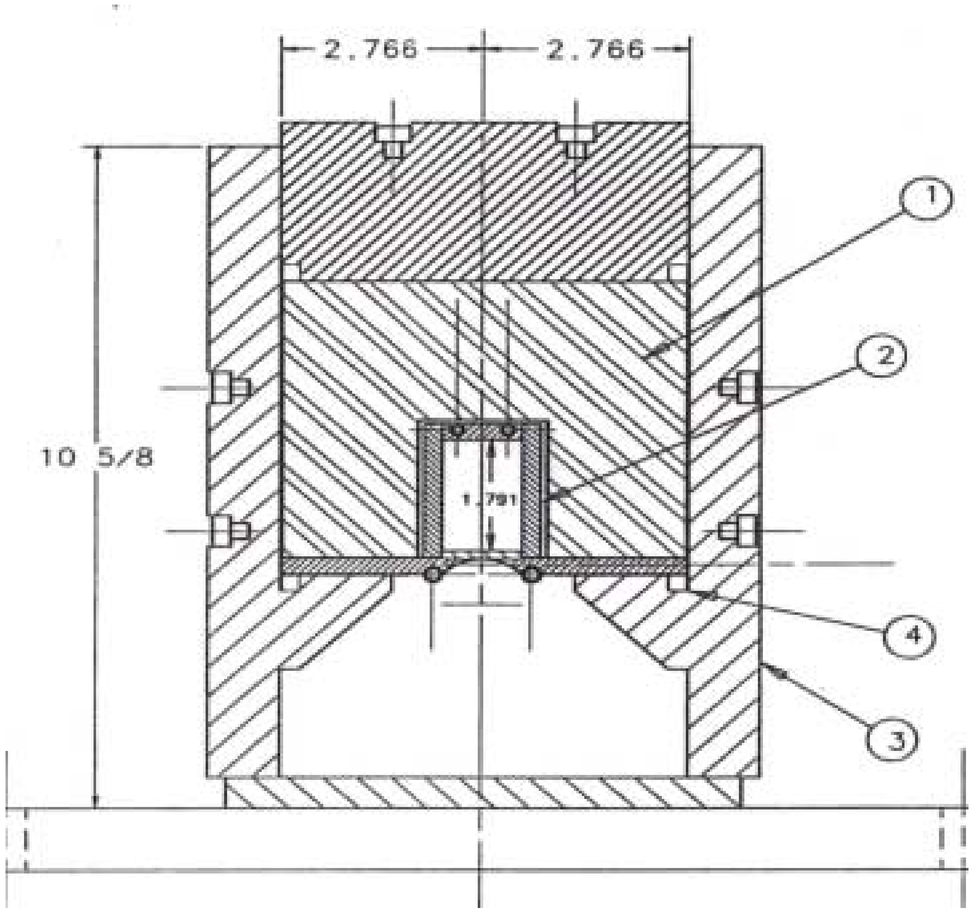

Figure 12.2. Booster Septum Cross Section

12.2.3. Local bump system (Injection Bump)

The extraction system design places the septum of Septum 1 at 10.14 mm outside the circulating beam. This placement minimizes the required extraction kicker strength. In order to maintain the nominal 120 π mm-mrad design aperture at injection, a local bump with an amplitude of ~23 mm at the upstream end of Septum 1 is required. The magnet strength required to accomplish this bump is not large, and it is expected that standard horizontal trim magnets will suffice. The first of these magnets is just upstream of Q607. The second and third magnets are installed just upstream of Septum 1 and QHL111 respectively. Table 12.1 lists the magnet parameters. Bump1, 2, and 3 are standard trim magnets and are dc powered; ramping is not required.

The amplitude of the bump at extraction is reduced by $1/(\beta\gamma)$ to about 1.5 mm. This residual bump amplitude adds to the effective thickness of Septum 1 and must be compensated for with the extraction kickers. Without this local bump, the septum would have to be placed at the 120 π mm-mrad aperture, and the kickers would have to kick ~96 mm instead of 31 mm.

Table 12.1. Magnet Parameters

Name	Number	Field (kG)	Inductance (μH)	Length (m)	Current
Kickers	10	0.225	1.419	1.0	2.45 kA
Septum 1	1	10.93	2.77	1.65	32.47 kA
Septum 2	4	13.049	$2.33 \times N^2$	1.35	40.23 kA-turns
Bump 1	1	+0.320		0.3	
Bump 2	1	–0.383		0.3	
Bump 3	1	–0.383		0.3	

12.3. Notcher system

Because the extraction kicker magnet fill time is 168 ns, a notch (gap) in the beam will be needed to prevent high losses on Septum 1. This is accomplished operationally by kicking out a few beam bunches at low energy. In the Fermilab Booster such a system has been operational for some time. The notch in the Booster is created using a very short (60 ns), 28 kV pulse through a standard extraction kicker magnet. This dumps the 400 MeV beam into the gradient magnets just downstream of the kicker but causes high local losses.

A different method of notch creation has been tried in the Booster and appears to work very well. The technique is to use a very weak kicker, repetitively pulsed to excite the beam (in the notch) at its tune frequency until all of the beam in the notch has been scraped out of the machine. In the case of the Booster, the kicker is pulsed about 85 times every 4^{th} turn since the horizontal tune is near the quarter integer. The pulse modulator is operated at 3 kV. Since the fractional part of the tune in both planes of the Proton Driver is near 0.4 the kicker would be pulsed every 5^{th} turn. The beam could be kicked in either plane. The idea is to cause the beam amplitude to blow up relatively slowly and allow the collimation system to absorb the excited beam. This technique is being studied in the Booster and is not yet operational. A major advantage of this system is that all the system components with the exception of the magnet are commercially available and are much cheaper than conventional high voltage thyratron devices.

Methods for notch creation external to the Proton Driver are also under study. Clearly, the preferred method would be that the notched beam be dumped external to the Proton Driver. However, even if a notch is created externally, a notcher internal to the Proton Driver is still required. The beam in a notch created externally is subject to debunching (the notch refills partially) during the adiabatic capture process and the internal notcher would be needed to "clean up" the notch.

Another example of cogging is where the Proton Driver is used in the multi-batch mode to fill the Main Injector. In this scenario a notch "cogging" scheme is needed in order to synchronize the notch in each successive batch with the extraction kickers and at the same time place the beam azimuthally correctly onto the Main Injector circumference. This cogging technique is similar to the cogging techniques used in the Main Injector and Tevatron to insure that the proton and anti-proton bunches collide at the proper place in the Tevatron, i.e., at the detectors. If a notch is created externally to the Proton Driver then the notch could potentially have to be cogged as much as half the machine circumference. This is possible, but the radial position excursions of the horizontal orbit would be large and would certainly be detrimental to the effectiveness of the collimation system. A more practical scheme is to wait until the beam is in the machine and then determine where on the circumference to create the notch to minimize the amount of cogging required. Such a system has been tested on the Booster but is not operational.

12.3.1. Fast kicker

The kicker magnet for the notcher system can be very weak compared to the extraction kickers, and will have a fill time considerably shorter than that of the extraction kickers. This scheme is still under study, and a design is not complete.

12.3.2. Beam dump

If the beam is absorbed by the collimation system, a special beam dump will not be required.

12.4. Abort system

It is not certain that an abort system is required or possible. The ideal abort system cleanly extracts the beam from the machine at all energies and transports it to an external beam dump. Such a system would be very difficult and prohibitively expensive to build. The reason is that all the magnets (kickers and septa) would have to track the machine energy. The apertures of the septa would have to be large enough to accommodate at least the 60 π mm-mrad injected beam. Assuming there are loss mechanisms, the beam likely will have a halo or emittance larger than 60 π mm-mrad, which would increase the required apertures even more. Further and most importantly, there really is no place in the lattice to install such a system. Therefore the abort system would have to be the operational extraction system.

Even a system that aborts the beam internally in the machine is potentially very hard to design. The reason is that different loss mechanisms have different growth rates. Detecting the different loss events in time to do something about them can be very difficult. For example, in the Booster, if the rf systems trip at ~1 GeV (this does happen and is easy to detect), the beam falls out in about 10 μs. This would be equivalent to about 3 revolutions in the Proton Driver. Reacting fast enough to properly dump the beam is questionable at best. Only some kind of fast kicker system could react fast enough to dump the beam in such an event. If such an event occurred in the Proton Driver without an abort system, the beam would simply spiral inward and one would expect that it would mostly be intercepted by the collimation system. The case of a high energy fast loss is of interest because it could be very hard on the collimation system. How well the collimation system works with the various fast loss scenarios needs further study.

There will be further study on an abort system that can safely dump the beam for at least some of the many beam loss scenarios.

12.4.1. Pulsed bumps

If one were to attempt to build an abort system, it likely would be built around a set of relatively fast pulsed magnets. These magnets would be arranged to form a local bump centered on a beam absorber/dump. The amplitude of the pulse would not be modulated with energy; rather it would be fixed and the pulse width would be tailored so that the pulse rise time is fitted to the loss times of the various beam loss mechanisms. At low energy the beam would hit the dump very quickly since it is being bumped at the highest rate of rise of the pulse. At high energy the beam would not hit the dump until the pulse reached full amplitude. For an rf loss mechanism such as described above this scheme would work well, but if some sort of high energy fast loss (fast with respect to the pulse rise time) occurred this system would not work.

12.4.2. Abort Beam dump

The design of such a beam dump has not been undertaken. More study is required.