

# Barrier RF Stacking

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**Abstract.** A novel wideband RF system, nicknamed the barrier RF, has been designed, fabricated and installed in the Fermilab Main Injector. The cavity is made of seven Finemet cores, and the modulator made of two bipolar high-voltage fast solid-state switches. The system can deliver  $\pm 7$  kV square pulses at 90 kHz. The main application is to stack two proton batches injected from the Booster and squeeze them into the size of one so that the bunch intensity can be doubled. High intensity beams have been successfully stacked and accelerated to 120 GeV with small losses. The problem of large longitudinal emittance growth is the focus of the present study. An upgraded system with two barrier RF cavities for continuous stacking is under construction. This work is part of the US-Japan collaborative agreement.

**Keywords:** Barrier rf, longitudinal stacking, high intensity protons

## INTRODUCTION

There are two major experimental programs at Fermilab at this time. One is Tevatron collider program Run2. Another is neutrino program including MiniBooNE (8 GeV protons from the Booster for neutrino production) and NuMI (120 GeV protons from the Main Injector for neutrino production.). In these programs, a key technical parameter is the proton beam intensity. The more protons we have, the more anti-protons and neutrinos we can generate. However, there is a bottleneck in the present accelerator complex, namely, the Booster. It is a machine more than 30 years old and has never been upgraded. Even with significant improvements in the past several years, it can only deliver about  $5 \times 10^{12}$  protons per cycle. The Main Injector, on the other hand, is a new machine and capable to accelerate much more protons than what the Booster can deliver. A logical solution, therefore, is to stack Booster beams in the Main Injector to increase the beam intensity. This is possible because the longitudinal acceptance of the Main Injector (about 0.7 eV-s) is larger than the Booster beam emittance (about 0.13 eV-s). There are two stacking schemes that Fermilab is working on. One is slip stacking, [Ref. 1] another barrier rf stacking. [Ref. 2-4] This paper will describe the progress on the latter.

There are two methods to carry out barrier rf stacking. One is adiabatic stacking. In this case, the beam is injected on the energy axis in the longitudinal phase space. It is then debunched, slowly compressed

by moving the rf barriers, recaptured by the main rf (53 MHz) and accelerated to 120 GeV. Another is fast stacking, in which the beam is continuously injected with a small energy error (i.e., off the energy axis) and folded by two rf barriers – one stationary, another moving – such that twice as many Booster batches can be injected into the Main Injector and the beam intensity is doubled. The second method was first proposed by J. Griffin. [Ref. 5]

## BARRIER RF SYSTEM

The barrier rf system consists of a cavity (figure 1) and a modulator (Figure 2). The cavity is made of seven Finemet cores. Finemet is a nanocrystal magnetic alloy patented by Hitachi. It has high magnetic permeability and low Q in the MHz range and is especially suitable for our application. Figure 3 shows a Finemet core. Figure 4 is a performance comparison between Finemet and ferrite 4M2. It is seen that Finemet can generate better square pulses than 4M2. The specifications of the Finemet cores are listed in Table 1. The main components of the modulator are a pair of bipolar high voltage fast switches. They are made by Behlke Company in Germany. Figure 5 shows one of the two switches. The specifications are listed in Table 2. This system is similar to an rf chopper used at HIMAC in Japan. [Ref. 6-8]



**FIGURE 1.** A barrier rf cavity in the Main Injector.



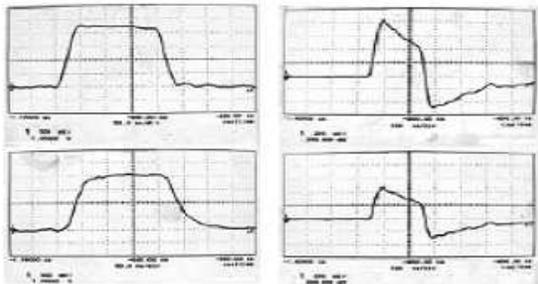
**FIGURE 5.** A high voltage solid-state fast switch HTS 161-06-GSM made by Behlke.



**FIGURE 2.** A barrier rf modulator.



**FIGURE 3.** A Finemet core FT3M made by Hitachi.



**FIGURE 4.** Performance comparison: Left –Finemet cores. Right – 4M2 cores. Upper ones are the primary voltage from the generator, lower ones the secondary voltage at the acceleration gap.

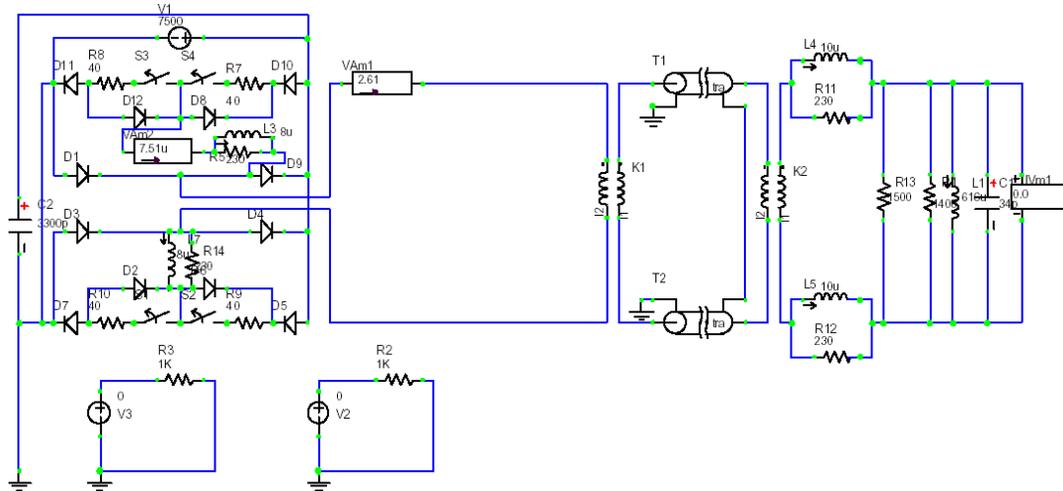
**TABLE 1.** Finemet core specifications

Type	FT3M
OD	500 mm
ID	139.8 mm
Thickness	25 mm
Inductance	56 $\mu$ H
Resistance	190 $\Omega$

**TABLE 2.** High voltage fast switch specifications

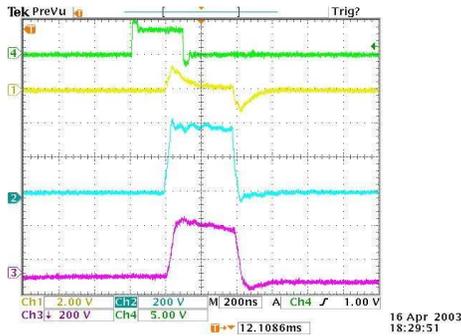
Type	HTS 161-06-GSM
Peak voltage	2 x 16 kV
Peak current	60A
Pulse width	300 ns
Pulse spacing	0.4 – 11 $\mu$ s
Repetition rate	90 kHz
Burst length	400 ms
Burst repetition rate	0.5 Hz

A particular concern in the design is radiation damage to the switches. The cavity is an inductive load, which would generate “ringing” after a single pulse. In order to minimize the ringing, the switches should be close to the cavity. However, the radiation level in the tunnel is high during machine operation, which could destroy the switches in a short time. Therefore, the switches must be far away from the beam line, which would lead to impedance mismatch between the load and the cable. A solution was found by using two transformers, one between the switches and the cable, another between the cable and the cavity. Figure 6 shows a complete circuit diagram for this system. The left part is the modulator, which is located in the rf gallery upstairs, and the right part is the equivalent circuit of the cavity, which is in the tunnel. Both are connected by 90-foot long cables.



**FIGURE 6.** Circuit diagram of the barrier rf system. The left part is a modulator in the rf gallery, the right part a cavity in the tunnel. Both are connected by 90-foot long cables.

Figure 7 shows the primary and secondary voltage pulses measured on a bench test. Due to stray capacitance in the system, one needs to pay special attention to the peak current and make sure it will not exceed the spec (60 A). Otherwise the switches could be destroyed and not be repairable.



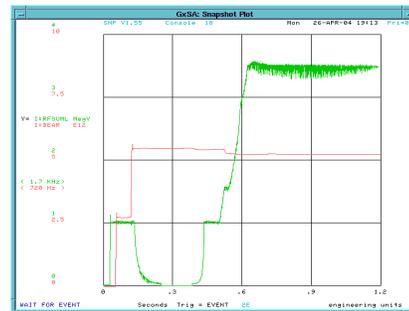
**FIGURE 7.** Bench test - from top to bottom: trigger signal (green), current (yellow), primary voltage (light blue) and secondary voltage (purple).

## BEAM EXPERIMENTS

After the installation of this system in the Main Injector in the summer of 2004, a series of beam experiments were carried out. The procedure is described as follows.

Two consecutive Booster batches are injected into the Main Injector and captured by the 53 MHz rf buckets. Each batch has 84 bunches for a length of 1.6  $\mu$ s. The two batches occupy a total length of 3.2  $\mu$ s,

which is 2/7 of the Main Injector circumference. The 53 MHz rf is then gradually turned off and the barrier rf turned on. So the beam is debunched and confined by the rf barriers. The barriers are slowly moved to squeeze the beam to half of its original size, i.e., from 3.2  $\mu$ s to 1.6  $\mu$ s. Then the 53 MHz rf is on again to recapture the beam and start acceleration. Figure 8 is an illustration of this process.

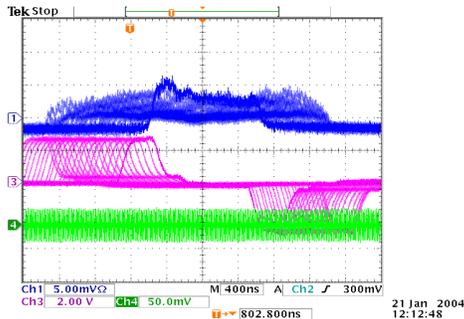


**FIGURE 8.** Barrier rf stacking process. Green – 53 MHz rf curve, red – beam intensity. At the bottom of the green curve, the barrier rf is on and moves to squeeze the beam.

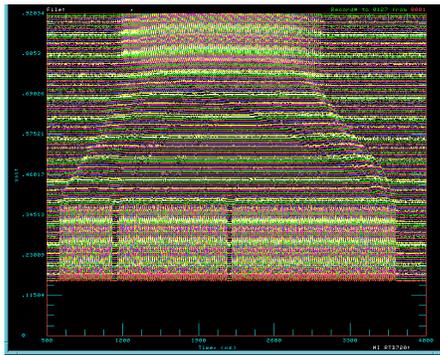
Figure 9 is a dynamic plot of the barrier rf voltage and the beam. It shows how the barriers move in and the beam gets squeezed. Figure 10 is a mountain view picture of the beam in the Main Injector. It shows clearly that the beam is squeezed to about half of its original size after stacking.

At the end of this process, the number of particles per bunch is twice as many as in the Booster beam. Figure 11 shows a beam of 8.3E12 is successfully accelerated to 120 GeV. This should be compared with

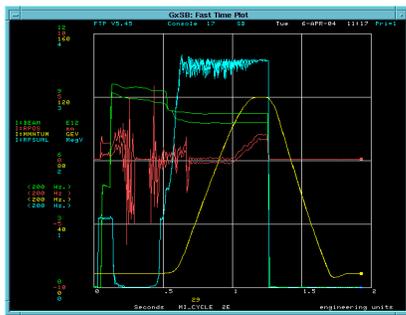
a normal Booster beam of  $5E12$ , an increase in intensity of about 60%.



**FIGURE 9.** Dynamic plot of barrier rf voltage (middle curve in purple) and beam (top curve in blue). When the barriers move in, the beam gets squeezed.



**FIGURE 10.** Mountain view picture of the beam. The vertical axis is time. The beam is squeezed to half size by moving the rf barriers.



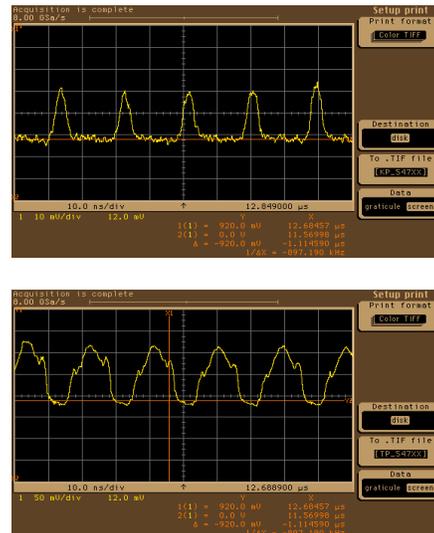
**FIGURE 11.** The green curves are the beam intensity during the cycle. After stacking,  $8.3E12$  protons are accelerated to 120 GeV, which is 60% higher than that in a normal Booster beam.

## DISCUSSION

The barrier rf system works to our satisfaction. The beam experiments are successful. They demonstrate that barrier rf stacking is a feasible way to increase beam intensities in a machine. The whole process takes less than 0.5 sec and can become part of the anti-proton production cycle without increasing the cycle time (2 sec).

Before implementing this scheme in Run2, however, the longitudinal emittance dilution problem will have to be addressed. The beam loss in Figure 11 (a big drop in the green curve) is due to scraping at the beginning of acceleration when the rf bucket size is shrunk.

Figure 12 shows the beam size after stacking. At high intensity, the emittance dilution is significant.



**FIGURE 12.** Beam spectrum after stacking: top – low intensity; bottom – high intensity.

A careful measurement gives 0.72 eV-s per bunch for a stacked high intensity beam at the early stage of acceleration (before transition). While a beam with such size can still cross the transition with almost no loss, it is too big for anti-proton production.

A possible source for the emittance dilution is beam loading. When the beam sits in between two barriers with the 53 MHz rf off, beam loading would cause energy tilt from beam head to tail. Such a tilted beam would lead to larger emittance growth than does a leveled beam. A possible cure is to use the

longitudinal damper in the Main Injector. This is the focus of our present study.

Another application of the barrier rf stacking is for NuMI during multi-batch operation. In this application, longitudinal emittance dilution is not as critical as in Run2. It would need two barrier rf systems, one stationary and another moving. We are in the process of fabricating a second barrier rf system and will install it in the Main Injector in 2005. When this system is in place, we will be able to employ the fast stacking method to accumulate 12 Booster batches in the Main Injector. (The normal operation calls for 6 batches.)

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