BARRIER RF STACKING AT FERMILAB*

W. Chou[#], J. Griffin, K.Y. Ng, D. Wildman, FNAL, Batavia, IL 60510, USA
A. Takagi, KEK, Tsukuba, Japan, H. Zheng, Caltech, Pasadena, CA 91125, USA

Abstract

A key issue to upgrade the luminosity of the Tevatron Run2 program and to meet the neutrino requirement of the NuMI experiment at Fermilab is to increase the proton intensity on the target. This paper introduces a new scheme to double the number of protons from the Main Injector (MI) to the pbar production target (Run2) and to the pion production target (NuMI). It is based on the fact that the MI momentum acceptance is about a factor of four larger than the momentum spread of the Booster beam. Two RF barriers - one fixed, another moving - are employed to confine the proton beam. The Booster beams are injected off-momentum into the MI and are continuously reflected and compressed by the two barriers. Calculations and simulations show that this scheme could work provided that the Booster beam momentum spread can be kept under control. Compared with slip stacking, a main advantage of this new method is small beam loading effect thanks to the low peak beam current. The RF barriers can be generated by an inductive device, which uses nanocrystal magnet alloy (Finemet) cores and fast high voltage MOSFET switches. This device has been designed and fabricated by a Fermilab-KEK-Caltech team. The first bench test was successful. Beam experiments are being planned.

MOTIVATION

A major performance parameter of the Fermilab Tevatron collider program Run2 is the total integrated luminosity. The goal is 10-15 fb^{-1} by 2007. There is also a neutrino program NuMI at Fermilab. It uses the 120-GeV proton beams from the MI to generate high intensity neutrino beams for a long baseline experiment at Soudan, Minnesota. This experiment will start in early 2005.

In order to reach the goals of the luminosity in Run2 and the neutrino flux in NuMI, one needs to increase the proton intensity on the production targets. In the present Fermilab accelerator complex, the Booster is a bottleneck that limits the proton intensity on the targets. The number of protons per cycle from the Booster cannot exceed 6×10^{12}. Otherwise the beam loss would become prohibitive.

To get around this bottleneck, one method is to use stacking. Namely, to put more than one Booster bunch into a Main Injector RF bucket. This is possible because the longitudinal acceptance of the Main Injector (0.4 eV-s) is larger than the longitudinal emittance of the Booster beam (0.1 eV-s). There are several possible ways to perform stacking. This paper introduces a new method based on employing a barrier RF system. The goal is to double the number of protons per bunch in the Main Injector, which would then give twice as many protons on the production targets per cycle. The average production rate of antiprotons and neutrinos would increase 50-60%. For more information about this study the readers are referred to Ref. [1].

METHOD

A straightforward way to do barrier RF stacking is as follows. Inject two Booster batches into the MI, confine them by RF barriers, and then move the barriers to compress the beam. When the beam size is reduced to half of its original length (i.e., to the size of one Booster batch), the main RF system (53 MHz) in the MI is turned on to capture the beam and starts acceleration. The drawback of this approach is that the compression must be slow (adiabatic) in order to avoid emittance growth. This would lengthen the injection process and thus reduce the number of protons on the targets per unit time.

A better way, which was first proposed by J. Griffin [2], works as follows. Inject the Booster beams into the MI with a small energy offset (a few tens of MeV). Two RF barriers are employed. One is stationary, another moving. The stationary barrier serves as a firewall preventing particles from penetrating. The moving barrier bends the beam of successive injections so that the total beam length is continuously compressed. A detailed analysis and simulations have been performed by K.Y. Ng and can be found in Ref. [3].

There is a difference between the barrier RF stacking for Run2 and that for NuMI. In Run2, the stacking process is 2-to-1, that is, two Booster batches compressed to the size of one. In NuMI, it is 12-to-6, that is, twelve Booster batches compressed to the size of six. Figs. 1 and 2 illustrate the two different stacking processes.

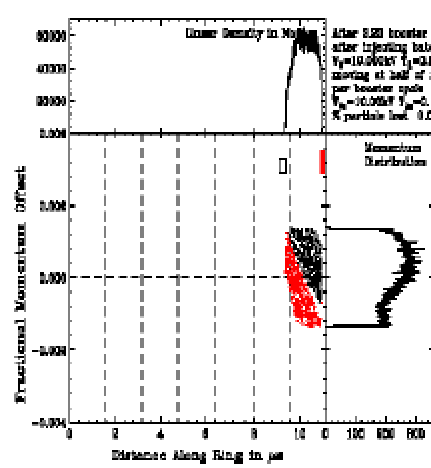

Figure 1: Barrier RF stacking for Run2. Two Booster batches are confined and compressed to the length of one. The two small rectangles, one red and one white, represent the two RF barriers.

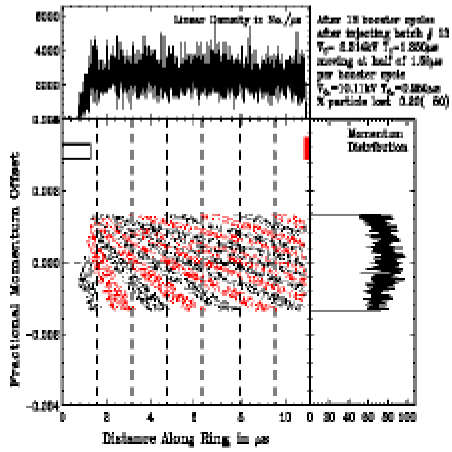

Figure 2: Barrier RF stacking for NuMI. Twelve Booster batches are confined and compressed to the length of six. The two small rectangles, one red and one white, represent the two RF barriers.

A BARRIER RF SYSTEM

An ideal barrier RF system is a wideband system rather than a resonant one, although the latter has also been used for this purpose [4,5]. One can use a wideband amplifier driving a 50 Ω gap to generate the required isolated voltage pulses, as is done in the Fermilab Recycler [6]. But this is an expensive approach. Instead, we adopt the design using an inductive device with a low quality factor, which is driven by high voltage solid-state switches.

System Description and Parameters

The system consists of an RF cavity and a power supply. It generates isolated square voltage pulses of both polarities. There are two different types of RF barriers:

- Stationary barrier: This is a series of bipolar pulses (+ and –) generated once every MI turn (11.2 μs), as shown in Fig. 3 (top). This barrier is similar to the one that was built and tested by a Fermilab-KEK-HIMAC team for an RF chopper [7].
- Moving barrier: This is a series of separated bipolar pulses shown in Fig. 3 (bottom). The spacing between +V and –V pulses varies from 0 up to 11 μs. They are also generated once every MI turn.

This barrier RF system works in burst mode. It generates a burst of pulses for a short period (150 ms for Run2). The time between two bursts is fairly long (about 2.2 sec). Therefore, the duty factor of this system is low. This makes the use of solid-state switches possible. Table 1 is the design parameters of this system.

Cavity

The cavity uses 7 Finemet cores. Finemet is a nanocrystal magnetic alloy developed by Hitachi. Compared with ferrite, it has higher permeability in the frequency range of several MHz and can stand a much higher magnetic field. Its Q value is less than one.

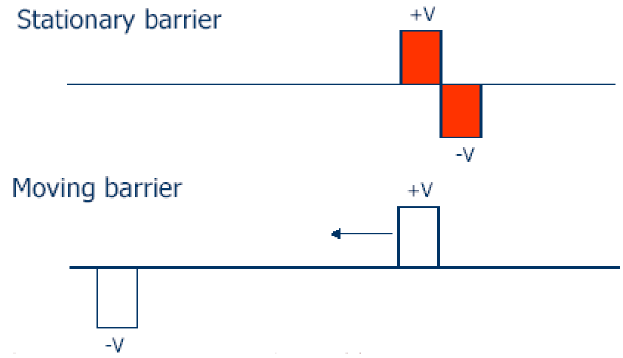

Figure 3: Two types of barriers.

Table 1: Barrier RF System Parameters

Pulse peak voltage	±6 kV
Pulse maximum length	0.3 μs
Pulse gap	0 - 11 μs
Max pulse repetition rate	100 kHz
Burst length	150 ms
Burst repetition rate	0.5 Hz

High-Voltage Fast Switch Circuit

The switches need to have high peak voltage and high peak current. Because the load is inductive, the switches must be bipolar in order to avoid flyback when the pulse is terminated. The HTS 161-06-GSM solid-state switches made by Behlke Co. are chosen. Fig. 4 is the circuit designed using SPICE. It has four switches forming a full bridge circuit. Snubber and damper circuits are applied to reduce the voltage flyback and peak current.

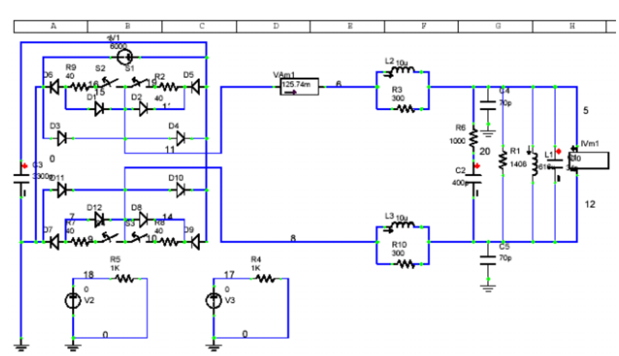

Figure 4: SPICE model of the circuit for the barrier RF power supply.

Bench Test

A bench test (with no beam) has been carried out on this system. The pulse pattern and peak voltage meet the specifications. The burst width reaches 200 ms. Fig. 5 shows the results.

*Work supported by Universities Research Association, Inc. under contract No. DE-AC02-76CH03000 with the U.S. Dept. of Energy.
†chou@fnal.gov

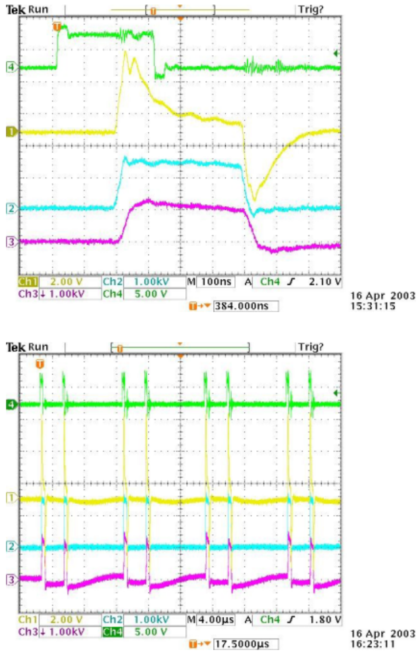

Figure 5: The four traces are, respectively, green – trigger, yellow – current, blue – switch output voltage, purple – cavity gap voltage. Top: single pulse. Bottom: a pair of pulses with a period of 10 µs. The distance between the twin peaks can be varied, forming a moving barrier.

DISCUSSIONS

Comparison with Slip Stacking

Stacking beams in the longitudinal phase space can also be achieved by the slip stacking method, which was first proposed at CERN in 1979 for the PS [8,9]. A main problem was beam loading. It caused large particle loss and emittance blowup at high beam intensities. This method is being reinvestigated at the Fermilab with an improved beam loading compensation technique [10].

The barrier RF stacking has smaller beam loading effects, because the peak beam current is lower and its 53 MHz component much smaller thanks to a debunched beam. This is a main advantage of this new method.

Emittance Dilution and Particle Loss

The simulation assumes 0.1 eV-s for the incoming Booster bunch longitudinal emittance. During the process, the Booster beam is debunched, compressed, stacked, rebunched and captured by the 53 MHz RF bucket. The final bunch has an emittance of 0.32 eV-s. So the blowup factor is 3.2, which is tolerable, because the MI acceptance is 0.4 eV-s. The particle loss in the simulation is negligible.

A Key Issue

In order to make the barrier RF stacking work, a key issue is to keep the energy spread ΔE of the injected beam small. Simulation shows that ΔE of the Booster beam must be below ±6 MeV so that the beam will be contained in the RF bucket after stacking. However, the ΔE of the present Booster beam is 2-3 times larger due to coupled bunch instabilities. Several measures are being tested to reduce the energy spread: (1) a longitudinal feedback system, (2) RF frequency modulation to provide Landau damping [11,12], and (3) bunch rotation.

Other Issues

This system will be installed in the MI for beam experiments. A potential concern is the radiation hardness of the switch, because it must be placed next to the cavity in order to minimize stray inductance and capacitance. Data are being collected.

Switch power dissipation for NuMI stacking is another concern, because the duty factor will be higher. One may use oil-cooled switches as a possible solution.

ACKNOWLEDGEMENT

This project is partially funded by the US-Japan collaboration in high-energy physics.

REFERENCES

[1] http://www-bd.fnal.gov/pdriver/barrier/
[2] http://www-bd.fnal.gov/pdriver/barrier/pdf/griffin.pdf
[3] K.Y. Ng, *"Doubling Main Injector Beam Intensity using RF Barriers,"* AIP Conference Proc. 642, p. 226 (2002); also see FERMILAB-FN-715, FERMILAB-TM-2183 (2002).
[4] M. Blaskiewicz et al., *"Barrier Cavities in the Brookhaven AGS,"* Proc. 1999 PAC (New York, USA), p. 2280.
[5] M. Fujieda et al., *"Magnetic Alloy Loaded RF Cavity for Barrier Bucket Experiment at the AGS,"* Proc. 1999 PAC (New York, USA), p. 857.
[6] G. Jackson, *"The Fermilab Recycler Ring Technical Design Report,"* FERMILAB-TM-1991 (1996).
[7] W. Chou et al., *"Design and Measurements of a Pulsed Beam Transformer as a Chopper,"* KEK Report 98-10 (September 1998); W. Chou et al., Proc. 1999 PAC (New York, USA), p. 565; Y. Shirakabe et al., Proc. 2000 EPAC (Vienna, Austria), p. 2468.
[8] D. Boussard and Y. Mizumachi, *"Production of Beams with High Line-Density by Azimuthal Combination of Bunches in a Synchrotron,"* IEEE Vol. NS-26, No. 3, p. 3623 (1979).
[9] J.P. Delahaye et al., *"Improved Recombination of the 20 PSB Bunches and Merging into 5 Dense Bunches in the CERN Proton Synchrotron,"* IEEE Vol. NS-26, No. 3, p. 3565 (1979).
[10] K. Koba and J. Steimel, *"Slip Stacking,"* AIP Conference Proc. 642, p. 223 (2002).
[11] C. Ankenbrandt et al., *"Longitudinal Motion of the Beam in the Fermilab Booster,"* IEEE Vol. NS-24, No. 3, p. 1449 (1977).
[12] B. Zotter, *"Damping of Coupled Bunch Instabilities by RF Frequency Modulation,"* FERMILAB-TM-2189 (November 2002).